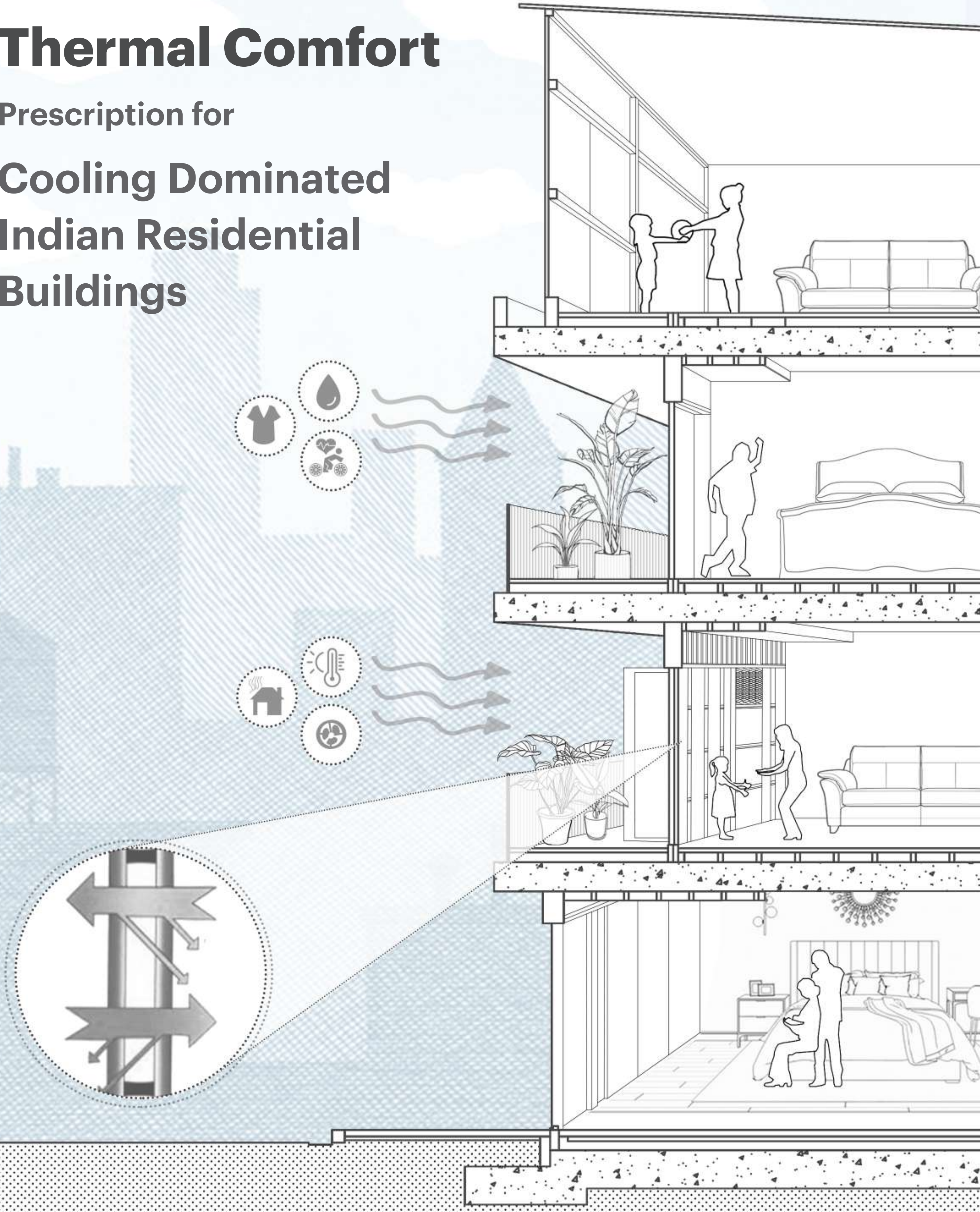
THE ENERGY AND RESOURCES INSTITUTE
Creating Innovative Solutions for a Sustainable Future

Mahindra LIFESPACES

Thermal Comfort

Prescription for

Cooling Dominated Indian Residential Buildings



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Foreword

The Housing for All mission by 2022 of the Government of India seeks to achieve the Sustainable Development Goals Target 11.1 “By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums”. The overall residential construction demand is expected to increase more than fourfold over 2005 levels as a result of meeting the urban housing shortage.

Mahindra Lifespaces and TERI through the Centre of Excellence jointly envisaged to build a greener urban future by developing energy-efficient solutions tailored to Indian climates. The project intends to provide credible information related to thermal properties of building materials in public domain. Under the five-year research scope, the CoE has created guidelines, toolkits, and handbooks to mainstream principles of energy-efficiency, thermal & visual comfort, and sustainable water use in habitat.

Furthermore, the lab established for testing of building material’s thermal properties is a SVAGRIHA 5-star rated facility that leads by example to achieve net-zero energy goals. The Centre is accredited by National Accreditation Board for Testing & Calibration Laboratories for thermal testing of building materials. The CoE has generated interest amongst government institutions, academia, and industry, globally. It is successfully established as a frontrunner in the materials market for testing instilling confidence in our research community.

The publication focuses on aspects related to daylighting and thermal comfort in affordable housing. Both issues are disregarded during design stages often leading to energy-intensive and uncomfortable indoor spaces. The reports specify quick rules and prescriptive requirements to aid designers make informed design decisions. It details out design processes and strategies to integrate daylighting and enhance thermal comfort in residential buildings.

We suggest reading the Part – 1 ‘Daylighting’: Prescription for affordable housing in India and Part – 2 ‘Thermal Comfort’: Prescription for cooling-dominated Indian residential buildings in conjunction as both issues cannot be addressed in isolation. However, it was essential to create two stand-alone parts distinctly explaining the fundamentals of daylighting and thermal comfort.

We hope that the designers and students find the reports of relevance and apply the principles in the buildings they create tomorrow.

Sanjay Seth
Senior Director- Sustainable Habitat
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1. Introduction

The primary purpose of human habitat is to provide the shelter, water, food, and space for occupant comfort and safety. With people spending more than 80% of their time indoors, the building characteristics and prevailing indoor environment ought to significantly impact them in all the possible ways. Dissatisfaction with indoor environmental quality (IEQ) (thermal comfort, acoustic comfort, visual comfort and indoor air quality) has a direct effect on the human health and productivity of the occupants, with thermal comfort exhibiting the strongest effect on human health.[1] [2]

> ***Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment.***
>
> - American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [3]

Average temperatures across India have risen by more than 0.5°C in 1960-2009, with statistically significant increases in heat waves. This corresponds to a 146% increase in the probability of heat-related mortality events of more than 100 people. India Meteorological Department (IMD) has attributed 40 per cent of all extreme weather-related deaths to heat waves in the year 2016.

Managing thermal comfort and minimising populations' exposure to heat stress will be necessary if cities are to be safe, resilient and sustainable (SDG 11). If strategies are not in place to protect populations from heat stress, it will impede progress towards income and productivity targets (SDG 8). Thermal regulation is also required for the provision of many health services (SDG 3). Access to affordable, reliable sustainable and modern energy (SDG7) for all could be put at risk by the added demand cooling places on energy infrastructure. If steps are not taken to reduce the emissions from cooling services (without preventing access to cooling for those that need it), climate targets will be put at risk (SDG13).

Thermal comfort guidance document by the World Health Organization emphasize that thermal comfort in the built environment is inextricably linked to human health and not merely satisfying the sense of satisfaction with the indoor thermal conditions primarily temperature [4]. With increasing population, raising temperatures and frequently occurring heat waves, thermal comfort in the built environment is bound to drive the health and wellbeing of India. In the light of the Government's commitment to construct 20 million affordable houses under Pradhan Mantri Awas Yojana by year 2022, pledging 'Thermal Comfort for All' in an energy efficient and climate friendly manner is vital. The goal of 'Thermal Comfort for All' needs to be integrated with the requirement of affordable housing. To achieve this, it is important to target improved thermal comfort through material choice, design and orientation planning in the development of improved energy efficiency in buildings. Designing energy efficient buildings for reduced the heat load, mainstreaming adaptive comfort approach, and cutting down the over-dependence on refrigerant based air conditioning are central to India's energy security and climate change mitigation efforts.

Human thermal comfort is a combination of a subjective sensation (how we feel) and several objective interactions with the environment (heat and mass transfer rates) regulated by the brain. Through thermoregulation process human body temperature is maintained within certain boundaries irrespective of widely ranging surrounding temperatures. The core temperature of the body remains steady at around 36.5–37.5 °C (or 97.7–99.5 °F). As presented in Figure 1. Heat transfer between human body and nearby surroundings takes place through:

- Convection (air currents over the body, creating a cooling effect by inducing some evaporation over the skin),
- Conduction (contact heat transfer with other surfaces, e.g. flooring, furniture)
- Radiation (instantaneous infrared heat transfer with any visible object or surface at a different temperature than a person's body, e.g. the sun, the floor, the walls of a room)
- Person's biological processes including evaporation (e.g. sweating, exhalation).

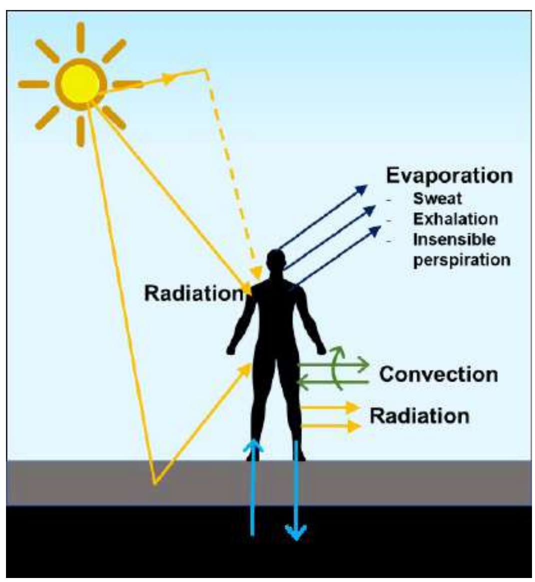

Figure 1: Heat exchange for human thermal comfort

Source: UC Berkley Centre for Built Environment)

As per ASHRAE Standard 55 [3], there are six primary factors that directly affect thermal comfort and are generally grouped in two categories:

- **Personal factors:** characteristics of the occupants (including clothing, metabolic rate)
- **Environmental factors:** conditions of the thermal environment (including indoor air temperature, mean radiant temperature, air speed and relative humidity)

In addition to the factors indicated above, there are additional factors affecting thermal comfort and heat dissipation from the body, such as food and drink, acclimatisation, body shape, fat, age and gender, and state of health.

Figure 2: Six primary factors used for defining acceptable thermal comfort in the built environment

1.1 Thermal comfort linkages with SDGs and other National priorities

Cooling is associated with economic growth and measures people's well-being, health, and productivity. Approximately 630 million slum dwellers may have access to electricity; however, the housing quality and income may not be sufficient to purchase or run even a fan[1]. Limited access to cooling solutions poses a severe threat to the lives of the people residing in hot climates like India with increasing population and temperatures.

India has the largest population-weighted Cooling Demand Days (CDD) globally (almost 30% of the world). At the same time, the penetration of cooling devices is extremely low (Approx. 6% of Indian households have an air conditioner). Thus, India's cooling demand is projected to grow exponentially in the years to come. This space and mobile air conditioning expansion could strain the country's electricity infrastructure and entail massive HFC emissions. It is thus imperative that India's cooling demand be controlled, met in the most energy-efficient way possible, and based on low-GWP (compared to HFCs) refrigerants[2]. Cognizant of the challenges posed by the growing

1 Sustainable Energy for All (SEforALL), Chilling Prospects: Providing Sustainable Cooling For All, 2018. https://www.seforall.org/sites/default/files/SEforALL_CoolingForAll-Report.pdf

2 Alliance for Sustainable Habitat, Energy Efficiency and Thermal Comfort for All. https://sheetalalliance.com/index.php/about-us

cooling demand; the Government of India has developed the **India Cooling Action Plan (ICAP)** with headline goals of:

» Reduction in cooling demand of 20-25% by 2037-38

» Reduction in cooling energy demand of 25-40% by 2037-38

» Reduction in refrigerant demand by 25%-30% by 2037-38

India's cooling-related challenges differ from the other countries due to great diversity in its geographical, climatic, social, and cultural features. Over 100 million people[3] live in squatter or slum-like settlements in India. As per the Asian Development Bank (ADB), the proportion of India's population living below the national poverty line is 21.9%. ADB also reported that about 21.23% of the country's population has a purchasing power parity (PPP) below $1.9 per day[4]. The urban slum dwellers are subject to greater cooling-related risks due to lack of access to basic amenities and higher heat stress attributed to urban heat island effect, population density, etc., in the urban settings.

It is essential to meet the cooling needs of the vulnerable communities with a rise in extreme heat events impacting health, productivity, and even survival. Additionally, the rising aspirations of the middle-income group may lead to dependence on inefficient appliances increasing energy consumption and related emissions with decreased levels of thermal comfort. Consequently, access to efficient and sustainable cooling solutions would underpin the nation's intent to realize SDG 3, 7, and 11.

In 2015, the Government of India launched several new urban schemes - Atal Mission for Rejuvenation and Urban Transformation (AMRUT), Pradhan Mantri Awas Yojana (PMAY), and the Smart Cities Mission (SCM). The primary aim of these schemes is to recast the country's urban landscape, make urban areas liveable, sustainable, smart, and inclusive while driving the economic growth of the country (Ministry of Urban Development, Government of India, 2015). While AMRUT focuses on improving the quality of life through providing sustainable essential services in 500 cities, Smart Cities Mission adopts an ICT -driven area-based development approach for providing a clean and sustainable environment through the adoption of 'smart solutions' for 100 cities across the country. In many ways, AMRUT and SCM guidelines have similar objectives as outlined in the Sustainable Development Goals (SDGs).

The strategic components of the Smart Cities Mission are city improvement (retrofitting), city renewal (redevelopment), and city extension (greenfield development), including a Pan-city initiative in which 'Smart Solutions' are applied, covering more extensive parts of the city. The focus is on sustainable and inclusive development by the creation of replicable models which act as lighthouses to other aspiring cities. The Smart City Mission also address issues about the provision of basic services, including clean water and sanitation, inclusive city planning, development of physical and social infrastructure, recycling and reuse of waste, use of renewables, etc. thereby

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[3] University of Cambridge. Fixing India's Slum Rehabilitation Housing, 2017. https://www.cam.ac.uk/stories/indias-slum-rehabilitation-housing

[4] Asian Development Bank (ADB), Basic Statistics 2019. https://www.adb.org/publications/basic-statistics-2019

aligning with the objectives of the SDG 11 which calls upon Governments to make cities and settlements inclusive, safe, resilient and sustainable. However, there is a need for a clear roadmap outlining ways to translate these goals into action for promoting sustainable cities across India.

The PMAY initiative of the Government of India aims to provide affordable housing to the urban poor with a target of building 10 million affordable houses by March 2022. The affordable housing construction in the country is leading by example in the use of alternative materials and innovative & sustainable solutions to provide thermally comfortable houses, especially to low-income groups. This sector is underwhelmed due to increased construction costs and a slowed economy resulting from the nationwide lockdown amidst the pandemic. While India undergoes rapid urbanization, providing 'Housing for All' (Pradhan Mantri Awas Yojana (PMAY) appears challenging. There is a need to dive deeper to understand the impacts of building at scale and mainstream principles of sustainability in all constructions.

Given the increasing infrastructure developments, this is likely to address the urban energy issues and improve the quality of public life. Additionally, as India's urban population increases, integrating energy-efficient and sufficient technologies in the built infrastructure to reduce carbon emissions and achieve low-carbon resilient cities becomes crucial.

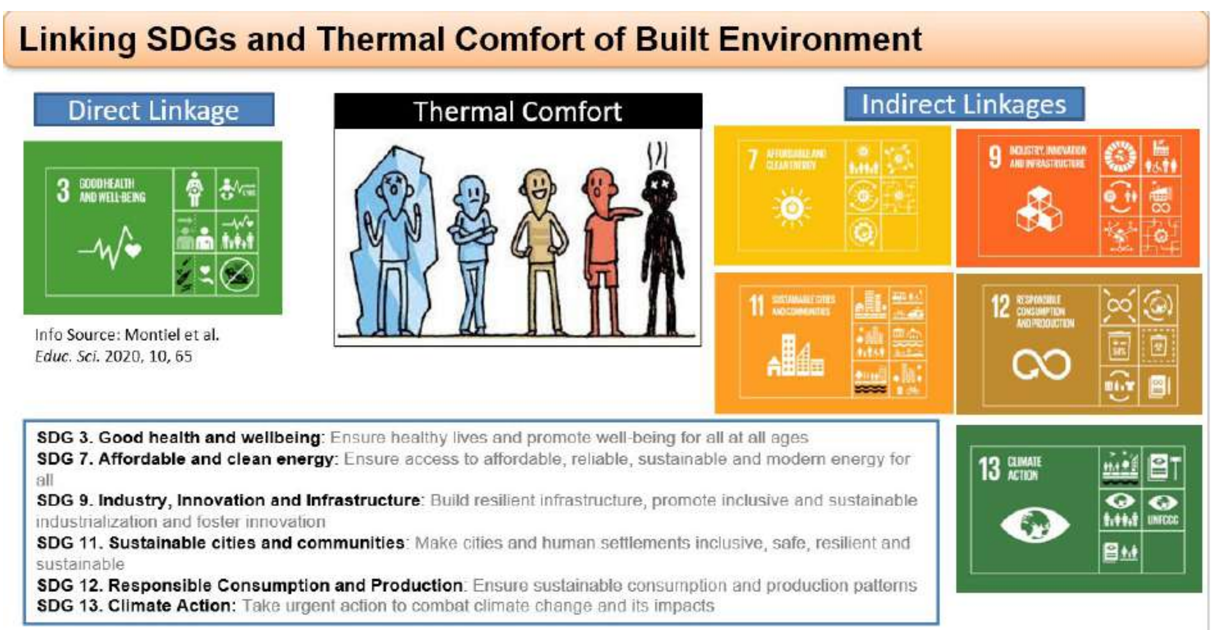


Figure 3: Direct and Indirect linkages of thermal comfort with Sustainable Development Goals (SDGs)

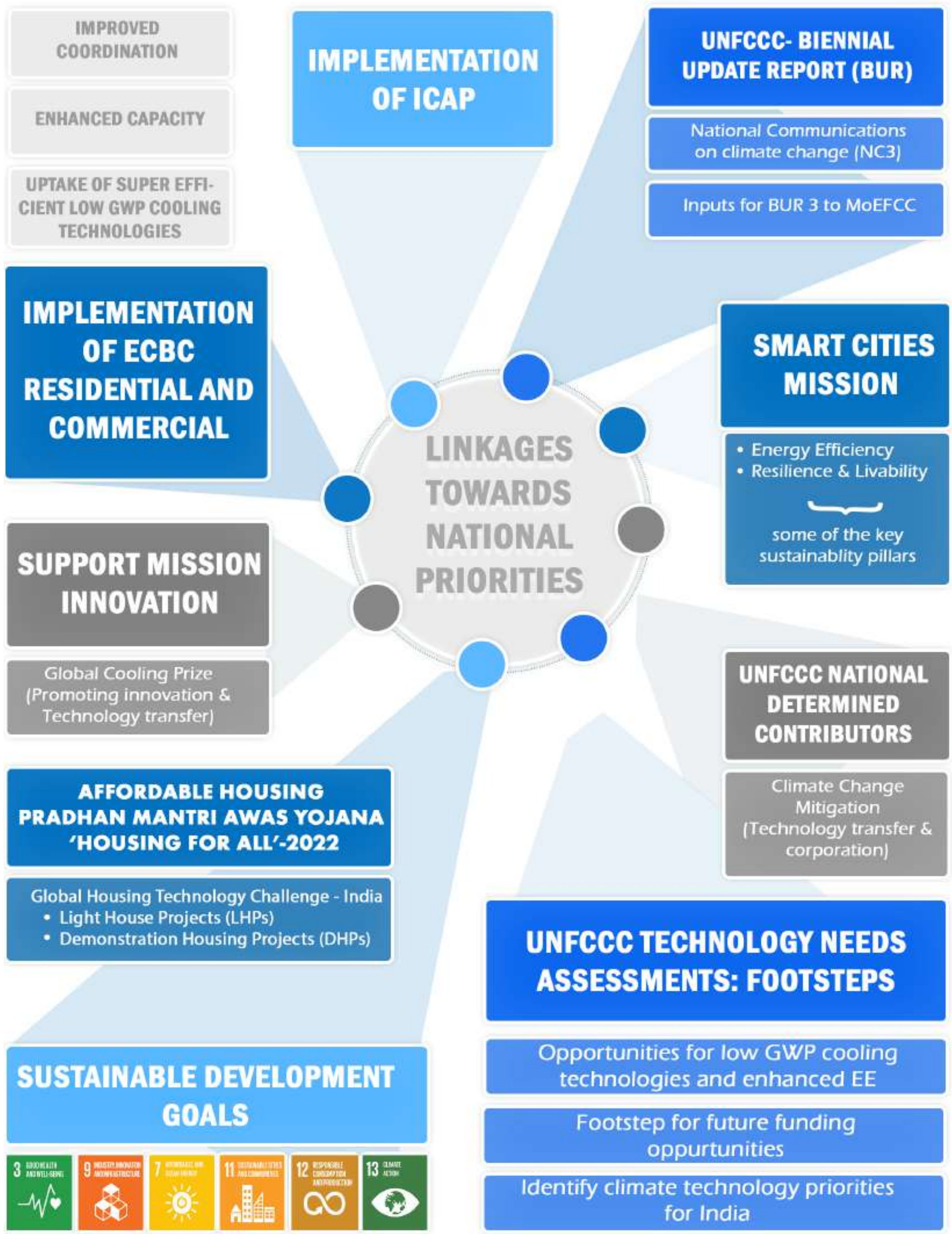


Figure 4: Thermal comfort linkages with national priorities

2. Thermal Comfort Approaches

“Heat balance approach” & “Adaptive approach” are the two approaches that widely used to determine the thermally acceptable/comfortable conditions of the built environment. These approaches are also employed to design the spaces for thermal comfort as well as evaluate the prevailing thermal comfort at post. Predicted Mean Vote and Predicted Percent Dissatisfied (PMV-PPD) model based on “Heat balance approach” is used to define thermal comfort conditions in climate controlled indoor spaces which include including air-conditioned buildings, centrally heated buildings etc. Adaptive comfort model is used for assessing the indoor thermal comfort in free running buildings which provide wide range of control to the occupants. “Heat balance approach” utilizes information from “climate chamber studies” to support its hypothesis, while the “adaptive approach” utilizes information from people during “field investigations” undertaken in actual buildings.

2.1 Heat Balance Approach

Heat balance approach of thermal comfort was introduced in the year 1967 for the first time [6]. Professor P.O. Fanger applied steady-state heat transfer model on the experimental results of thermal comfort study performed on 1296 young Danish students seated inside a controlled climate chamber [7]. This approach describes *“thermal discomfort”* as the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e., neutral) comfort for a particular activity. The human body generates heat, exchanges heat with the surroundings and loses heat by diffusion and evaporation from the body. Steady-state experiments showed that cold and warmth discomfort is strongly related to the mean skin temperature and skin wittedness, respectively.

As per Heat Balance Approach:

“An imbalance between the constant core body temperature and outdoor thermal environment produces a state of thermal discomfort.”

Fanger proposed empirical relations to evaluate comfort levels from the database collected during climatic chamber experiments conducted on European subjects. “Predicted Mean Vote” (PMV) is a quantitative function of four environmental parameters, i.e., air temperature, air velocity, mean radiant temperature, relative humidity, and two personal variables, i.e., activity & clothing insulation [6]. PMV is an index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale.

If the score resulting from PMV equation converges to zero, the satisfaction of the office occupants from thermal environment is at the maximum level.

PMV within a band of ±0.5 (corresponding to 90% acceptability) and ±0.85 (corresponding to 80% acceptability) is considered comfortable and beyond this limit, occupants are thermally dissatisfied.

Percentage of people dissatisfied (PPD) predicts the percentage of people who are likely to be dissatisfied with an environment. As the PMV moves away from 0, the PPD increases. 100" % PPD would indicate that 100"% of people would be expected to be dissatisfied with the thermal environment.

PPD below 10"% is recommended for acceptable indoor environment.

Figure 5 presents the graphic relation between PMV-PPD indices. PMV-PPD model of thermal comfort fails to consider the effect of local meteorological conditions, as well as cultural, social, behavioral and lifestyle of people on thermal comfort; therefore, its applicability has been constantly questioned in tropical countries like India.

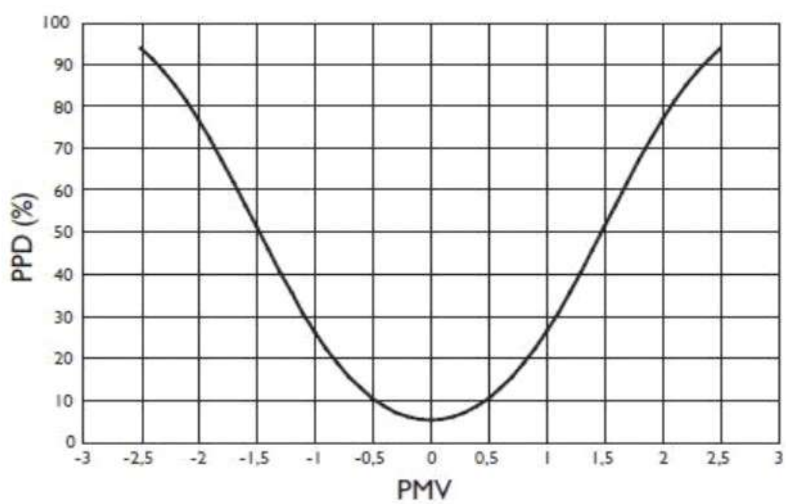


Figure 5: Percentage Predicted Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV)

2.2 Adaptive comfort approach

Adaptive approach of thermal comfort was first introduced by Humphreys and Nicol [8] to predict the comfort conditions for naturally ventilated buildings.

Adaptive comfort principle states that "if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort."

This approach recognizes that the thermal comfort of the occupant is more significantly associated with contextual factors including recent experiences in their thermal history. The generic term "adaptation" might broadly be interpreted as the gradual diminution of the occupant's response to repeated environmental stimulation [9] The results of the field study conducted in actual buildings are used to determine the thermal neutrality and acceptable temperature bandwidth in a particular climatic condition. Figure 6 presents the three elements of thermal adaptation to indoor environments. The adaptive approach to thermal comfort established a theoretical framework including behavioural, physiological, and psychological adaptive processes [10].

Adaptive comfort model relates indoor acceptable temperature to outdoor meteorological or climatological parameters.

Thermal comfort prediction through adaptive approach has also been found accurate and widely acceptable for air conditioned and mixed mode buildings as this approach takes in to account the various adaptations of building occupants. Adaptive models of thermal comfort have been incorporated in many standards such as ASHRAE Standard 55, European Standard 15251, ISO Standard 7730 and Indian National Building Code.

Figure 6: Thermal adaptation to indoor environment

3. Relevant Standards and Codes

3.1 ASHRAE Standard 55- 2017: Thermal Environmental Conditions for Human Occupancy

ASHRAE Standard 55 is the most widely adopted standard for thermal comfort studies across the world.

ASHRAE defines thermal comfort as that condition of mind which expresses satisfaction with the thermal environment, and it is assessed by subjective evaluation.

As presented in Figure 7 ASHRAE 55 defines "thermal comfort zone on a psychrometric chart, specifying boundaries of operative temperature and humidity for sedentary activity (1–1.3 met) and defined clothing (0.5–1 clo)." The "PMV model" used in ASHRAE Standard 55, while suggesting thermal comfort zone, considers the air velocity up to 0.2 m/s whereas, the "Graphical Elevated Air Velocity method and the Standard Effective Temperature (SET*) method" allows the use of high air velocities to offset in indoor temperature for comfort improvement. ASHRAE 55 suggests when control of local airspeed is provided to occupants; the maximum airspeed shall be 1.2 m/s (see Figure 8). It leads to the condition of no paper blowing due to the use of ceiling and pedestal fans at the location of the occupants doing light office work.

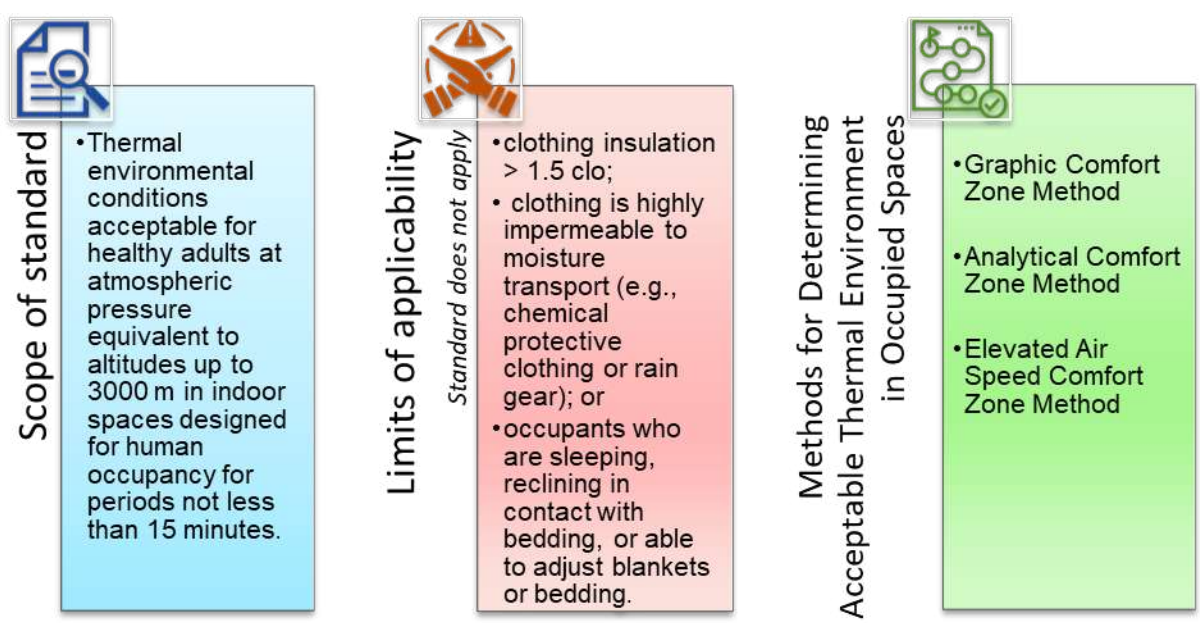


Figure 7: Scope, limits and thermal comfort methods of ASHRAE 55

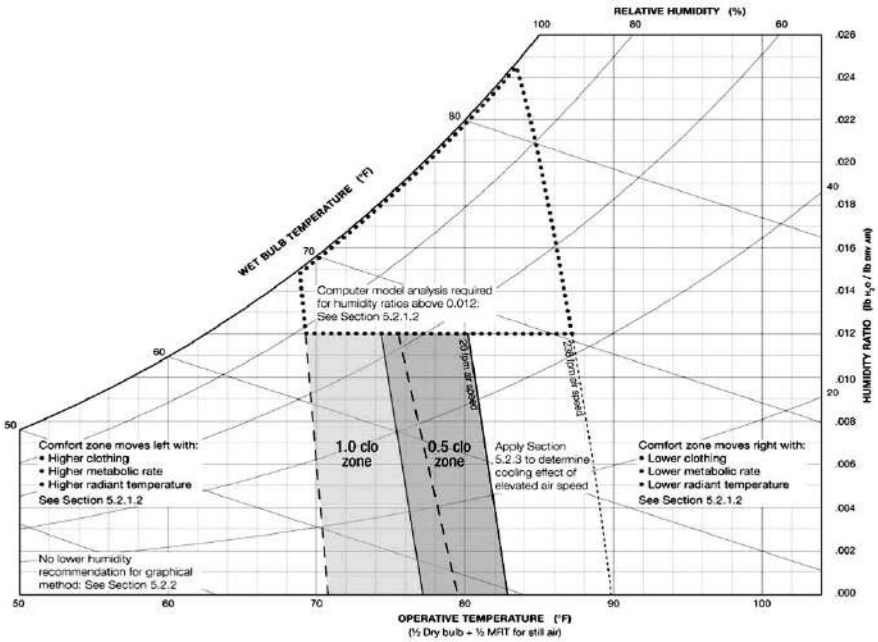


Figure 8: Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity (applicable for: 1.0 <met < 1.3; 0.5 < clo < 1.0)

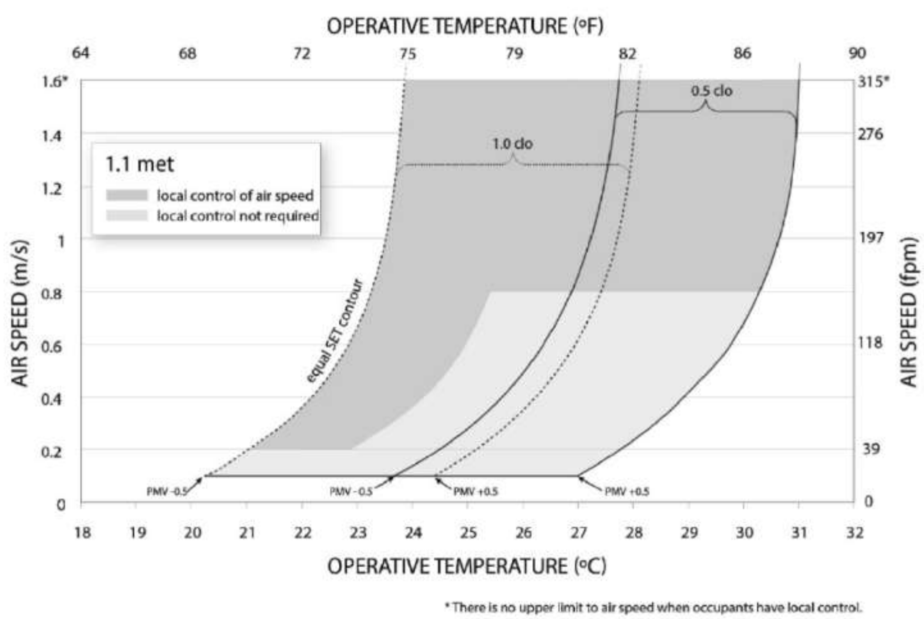


Figure 9: Acceptable range of operative temperature and airspeed for comfort

ASHRAE Standard 55 introduced the adaptive comfort model in its 2004 revision. The adaptive chart relates indoor comfort temperature to prevailing outdoor temperature and defines zones of 80 per cent and 90 per cent occupant satisfaction. ASHRAE Standard 55 introduced the prevailing mean outdoor temperature as the input variable for the adaptive model. It is based on the arithmetic average of the mean daily outdoor temperatures over no fewer than seven and no more than 30 sequential days prior to the day in question. In order to apply the adaptive model, there should be no mechanical cooling system for the space; occupants should be engaged in sedentary activities with metabolic rates of 1–1.3 met; and a prevailing mean temperature greater than 10°C and less than 33.5°C.

Adaptive comfort model as per ASHRAE 55	T_{comf}=0.31T_pma +17.8
80% Acceptability Upper limit (Eq + 3.5)	T_{comf}=0.31T_pma +21.3
80% Acceptability Lower limit (Eq - 2.5)	T_{comf}=0.31T_pma +14.3
90% Acceptability Upper limit (Eq + 2.5)	T_{comf}=0.31T_pma +20.3
90% Acceptability Lower limit (Eq - 2.5)	T_{comf}=0.31T_pma +15.3

T_{comf}: Indoor comfort temperature corresponds to acceptable operative temperature

T_{pma}: Prevailing mean outdoor air temperature

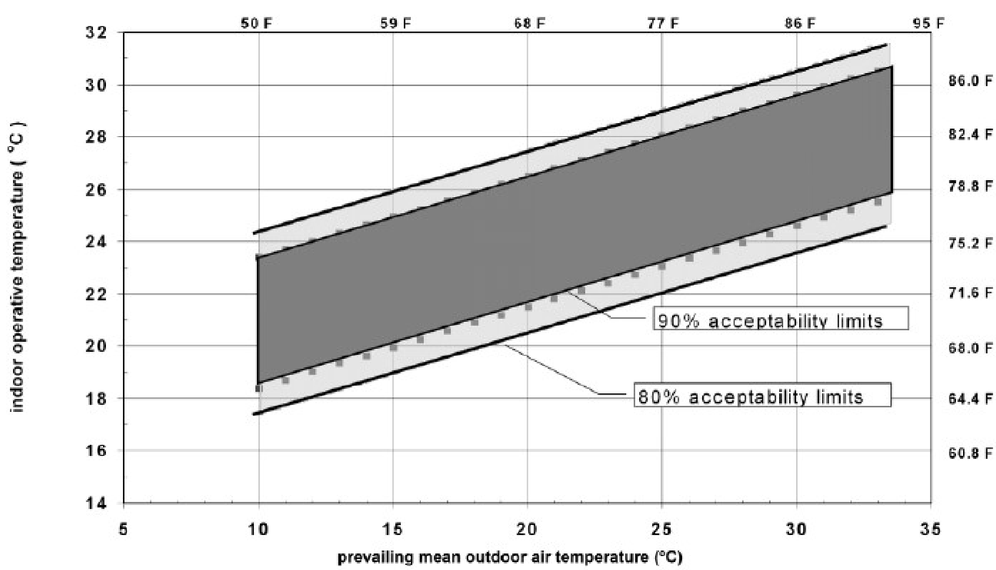


Figure 10: Acceptable operative temperature ranges for naturally conditioned spaces as per adaptive comfort model

3.2 ISO 7730 [11]

Thermal comfort standard developed by International Organization for Standardization (ISO) entitles to "ISO 7730 (2005): Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD and Local Thermal

Comfort Criteria". ISO 7730 presents a standard method for evaluation of the overall thermal sensation and the degree of thermal discomfort. This standard is mainly used in Europe and applies to moderate thermal conditions. Based on the PMV-PPD values, this standard sort indoor thermal environment into three categories (see Table 1). It recommends a PPD of 10% for local thermal discomfort. The standard defines the local clothing habits for indoor comfort but method for calculation of clothing ensembles is missing. This standard also provides an acceptable indoor environment that can be extended with increased indoor airspeed using a graphical method (see Figure 11).

Table 1: Categories of the thermal environment

Category	Thermal state of the body as a whole		Local discomfort			
	PMV	PPD (%)	DR (%)	Percentage Dissatisfied by		
				Radiant asymmetry	Vertical air temperature difference	Warm or cool floor
A	-0.2 <PMV <0.2	< 6	< 10	<5	< 3	< 10
B	-0.5 < PMV < +0.5	< 10	< 20	<5	< 5	< 10
C	-0.7 < PMV < +0.7	< 15	< 30	< 10	< 10	< 15

DR-Draught;

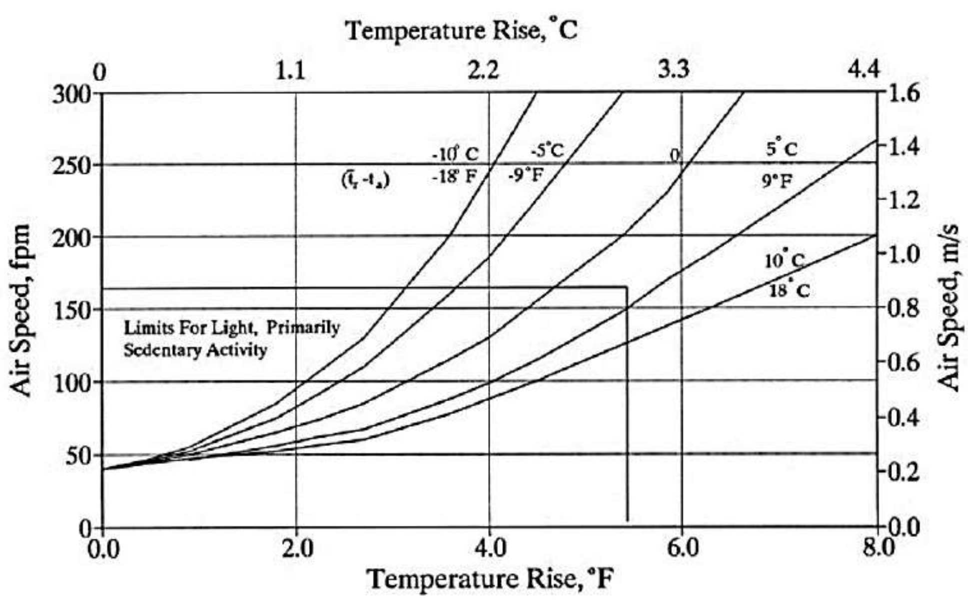


Figure 11: Acceptable range of operative temperature and airspeed for comfort using Graphical method

3.3 National Building Code of India (NBC 2016) [12]

National Building Code (NBC) of India is a standard which unifies the building regulations all over the country. Bureau of Indian Standards (BIS) launched NBC in 1970 as a guideline for buildings construction, operation and maintenance. After the National Building Code of India was published in 1970, various stakeholders made a large number of recommendations, and as a result, the standard was revised at regular intervals in the years 1983, 2005 and 2016. According to NBC-2016, air conditioning systems for interior spaces intended for human occupancy shall be sized for not more than 26 ºC for cooling and not less than 18 ºC for heating. As per the latest edition published in the year 2016, the adaptive comfort model was first introduced duly emphasizing on the indoor thermal comfort, occupant well-being, and energy-efficient operation of HVAC. Adaptive comfort model for the design and operation of NV and MM buildings by Manu et al. [13] was also added in NBC-2016. Adaptive comfort model for AC buildings by Dhaka and Mathur [14] was also included in the standard.

Table 2: Adaptive thermal comfort equation for determining acceptable indoor conditions as per NBC 2016

Type	Adaptive comfort model as per NBC 2016
Naturally ventilated building	$T_{in}=0.54T_{rm}+12.83$ 90% acceptability range: ±2.38 °C
Mixed mode building	$T_{in}=0.28T_{rm}+17.87$ 90% acceptability range: ±3.48 °C
Air-conditioned building	Air temperature-based approach: $T_{in}=0.078T_{rm}+23.25$ 90% acceptability range: ±1.5 °C
	Standard Effective Temperature based approach: $SET_{in}=0.014T_{rm}+24.53$ 90% acceptability range: ±1.0 °C

Tin: Indoor operative temperature (in °C) is neutral temperature
Trm: 30-days running mean outdoor temperature
SETin: Standard effective temperature (in °C) is neutral temperature

3.4 Eco-Niwas Samhita (Energy Conservation Building Code for Residential Buildings)

Ministry of Power and Bureau of Energy Efficiency (BEE) launched Eco-Niwas Samhita 2018 (Part I: Building Envelope) for regulating energy efficiency in residential buildings through residential building envelope related benchmarks. Part 1 sets the minimum building envelope performance standards to limit heat gains (for cooling dominated climates) and to limit heat loss (for heating dominated climates), as well as for ensuring adequate natural ventilation and daylighting potential.

the code provides design flexibility to innovate and vary important envelope components such as wall type, window size, type of glazing, and external shading to windows to meet the compliance. Recently Eco-Niwas Samhita 2021 (Code Compliance and Part-II: Electro-Mechanical and Renewable Energy Systems) is developed to set the minimum benchmark to achieve energy efficiency in residential buildings. The code is focused on electro-mechanical and renewable services in addition to the envelope parameters as prescribed in Eco Niwas Samhita 2018.

3.5 ISHRAE Indoor Environmental Quality Standard – 10001:2019

ISHRAE released the first-ever Indian standard on Indoor Environmental Quality (IEQ) in 2016, which was subsequently updated to ISHRAE Standard 10001: 2019. This standard identifies thermal comfort, indoor air quality, visual comfort and acoustic comfort as four critical elements of IEQ. These elements have been covered by defining their respective threshold levels of IEQ parameters. Three levels for defining threshold values have been created: Class A (Aspirational), Class B (Acceptable) and Class C (Minimum acceptable). The defined threshold levels become more stringent for Class B and Class A. This standard is applicable for both residential and commercial buildings of either naturally ventilated, mixed-mode or air-conditioned types. The standard also specifies IEQ testing methods, instrument specifications, and an occupant satisfaction survey.

4. Recommendations for Improving Indoor Thermal Comfort

Indoor thermal conditions up to a certain extent can be improved by judicious selection of building components, optimum orientation of building layout and proper selection of shading devices.

4.1 Building design

Architectural design features including form, orientation, shape etc. strongly affect the indoor thermal conditions of built space. The vast majority of a building's performance is influenced by its size, shape, orientation, massing, and fenestration. Climate responsive building design yields best comfort conditions to its users in the most efficient and economic ways. In predominantly hot regions, buildings should be ideally oriented to minimize solar gains; the reverse is applicable for cold regions. The building form determines the air flow pattern around the building directly affecting its ventilation. Optimal building form depends on the Compactness (Surface Area to Volume Ratio i.e., S/V ratio) and Perimeter to Area ratio (P/A). In hot & dry regions and cold climates, building's shape needs to be compact to reduce heat gain and losses, respectively. Building forms with shorter depths can facilitate cross ventilation throughout the building.

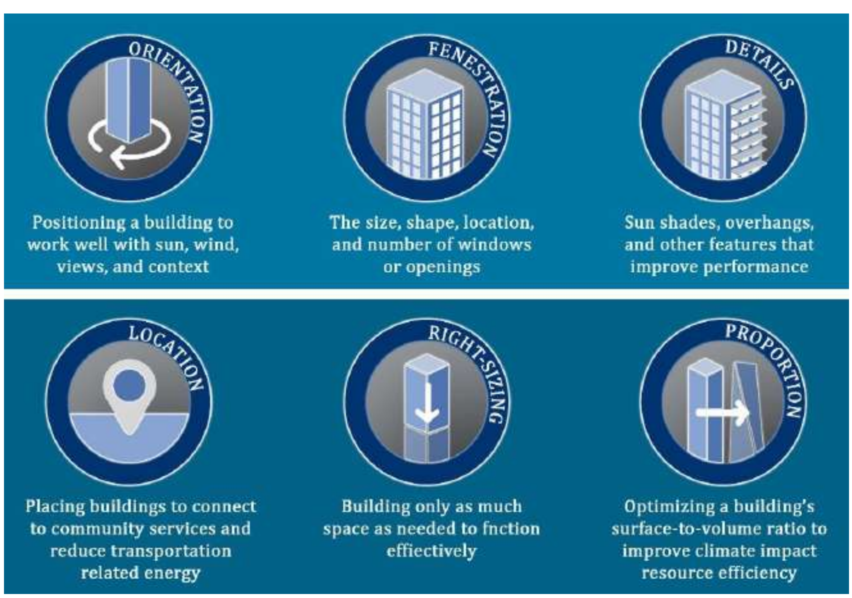
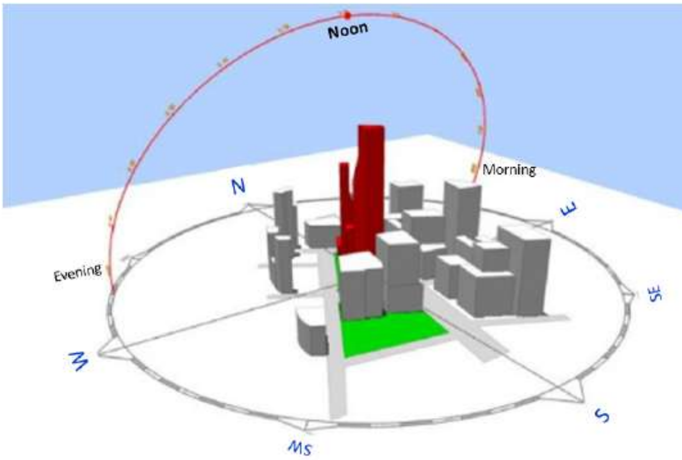


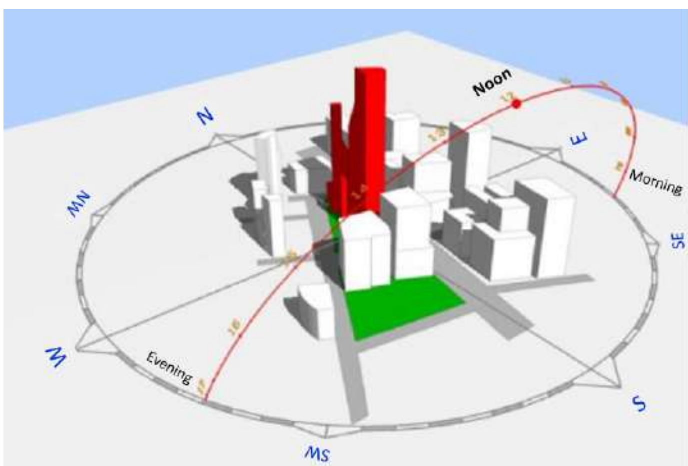
Figure 12: Architectural design features of a building



(a)

SUMMER SUN

- Sun path at a high angle
- Sun position is North to E-W axis
- Easy shading of south facade from high angle sun
- Glare free daylight on north facade
- Summer comfort strategy:
- Minimize solar heat gains Promote heat loss and ventilation



(b)

WINTER SUN

- Sun path at a low angle
- Sun position is South to E-W axis
- Solar penetration will be highest on south facing facades
- Winter comfort strategy:
- Maximize solar heat gains
- Minimize heat loss

Figure 13: (a) Summer sun path, and (b) Winter sun path, in central part of India

Source: https://fairconditioning.org/knowledge/passive-design/form-and-orientation-2/, Accessed on 16th November 2021)

Table 3: Key considerations for opting the right orientation

North facade receives very little direct radiation. Only in summer morinings and evenings					
South facade is highly exposed in winter, but less in summer					
East and West facades receive high amount of radiation both in summer and winter					
Horizontal surface (roof) receives the greatest intensity					
Climate	**Design Considerations**				
Hot & Dry	Block the sun	Maximize daylight	Design for Natural Ventilation	Increase Relative Humidity in Summer	Maximize the use of free solar heat in Winters
Warm & Humid	Block the sun	Maximize daylight	Design for Natural Ventilation	Protect against Driving Rain	Build tight
Composite	Block the sun	Maximize daylight	Increase Relative Humidity in Summer	Maximize the use of free solar heat in Winters	Design for Natural Ventilation
Temperate	Block the sun	Maximize daylight	Build tight	Allow Natural Ventilation for Night Cooling	

4.2 Recommendations for Cooling-dominated regions

» Larger facades of building oriented towards north-south are preferred for minimum solar heat gains. The best arrangement for minimizing the solar heat gains is to orient the long axes of the building in the east-west direction. Providing buffer spaces, shaded walls, staircase etc. on the south side is recommended for better comfort.

» The prominent wind direction in most parts of India is from the west or the east, for most of the year. Main walls and windows should face the prevailing (cool) wind direction in order to allow maximize cross-ventilation of the rooms [15].

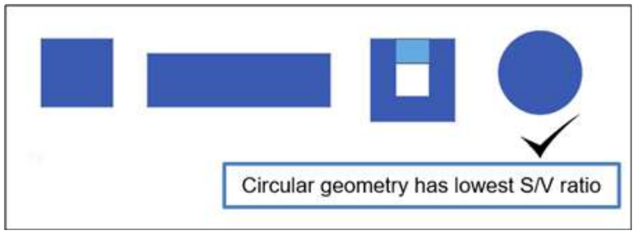
- Buildings oriented at an angle ±45° to the prevailing wind direction is found best for utilizing the wind flow.

» Optimal Building Form: Building form determines the volume of space inside a building that needs to be heated or cooled.

Surface to volume (S/V) ratio of the building is a measure of building compactness. It is the ratio for the external surface area of the building to the treated floor area. It is also known as 'heat loss form factor'.

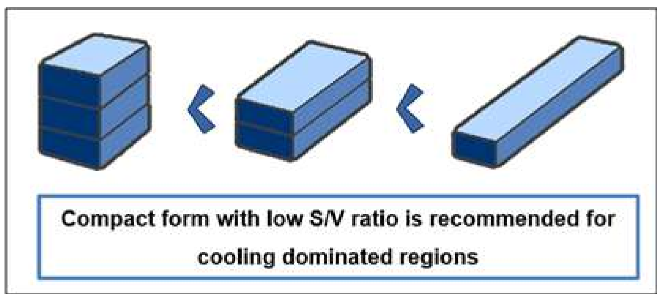
Small S/V ratio is an indicator of high compactness.

The circular geometry has the lowest S/V ratio thus the conduction gains from the building envelope as well as solar gains from windows are least in comparison to other building geometries.



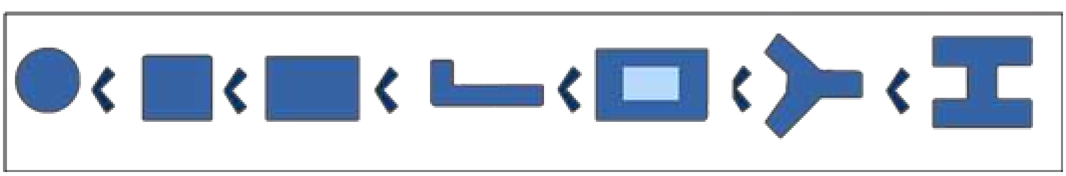
Increase compactness by reducing surface area for the same volume.

A rectangular form with a longer axis along the north-south is the preferred orientation.



P/A (Perimeter/Area) ratios indicate radiative gains or losses and efficient ventilation.

Low P/A ratios are suitable for cooling dominated regions especially for hot & dry climates [16].



Shape	Suggested P/A ratios [16]
Circle	0.88
Square	1
Rectangle	1.05
H	1.13
L	1.25

» Best possible typology for high rise buildings: Tower typology, Linear typology and, Linear double-loaded corridor typology are three broadly classified typologies of multi storey residential buildings in India [17].

- Proper choice of building shape for a particular orientation can reduce the solar radiation exposure by 20%–40%.

Assuming the orientation of the larger façade in a north and south direction), the preference of typologies in terms of reduced solar radiation exposure in the hot & dry, composite and warm & humid climates of India are [17][18]:

Preference 1: Linear double-loaded corridor typology [17] [18]

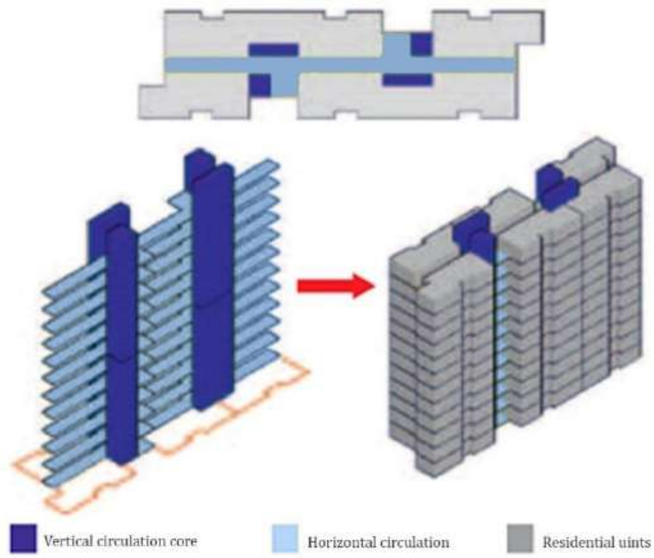


Figure 14: Liner double-loaded corridor typology

Preference 2: Linear typology [17] [18]

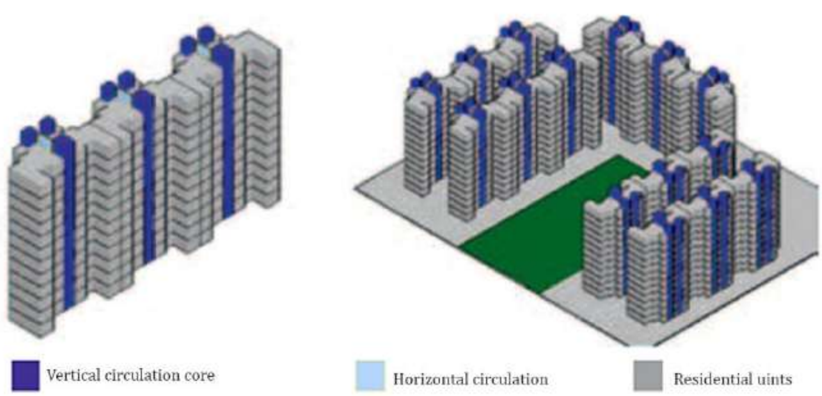


Figure 15: Linear typology

Preference 3: Tower typology [17] [18]

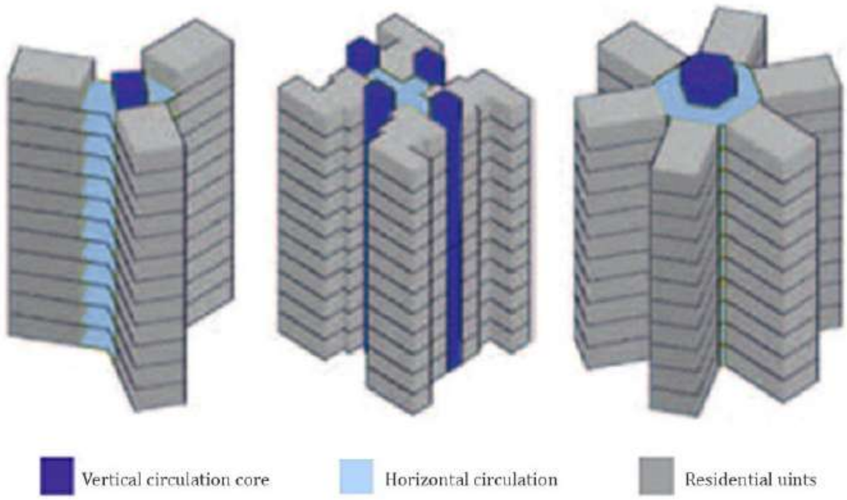


Figure 16: Tower typology

4.3 Energy efficient building envelope

Building envelope components such as wall, roof and fenestration act as an interface between outdoor and indoor environment. Correct building design and use of energy efficient building materials can substantially improve the indoor thermal comfort along with reduced energy consumption and enhanced occupant health, wellbeing & productivity. The thermal performance of a building envelope represents its capacity to regulate heat gain and loss during summer and winter season respectively.

Overall heat transfer coefficient or U-value of glass/walls/roof: U-value defines the amount of heat that gets transmitted through a unit area of a material for a unit difference in temperature. The U-value is therefore also called *thermal transmittance*. Determining U-value is particularly important for the building's envelope. The components of building envelope such as, windows, masonry, plaster or other insulating materials serve as heat transmitting solid mediums. The combined effect of these components should be to prevent the heat transfer between interior of the building and the environment as much as possible. As shown in the Figure 17 below, under steady state condition for one dimensional heat flow:

(Rate of heat convection into the wall=rate of heat conduction through the wall= rate of heat convetion from the wall)

Or

$$Q = h_1 A (T_A - T_1) = kA \frac{(T_1 - T_2)}{L} = h_2 A (T_2 - T_B) \qquad (1)$$

Where;

L is the thickness of the plane wall, A is the surface area of the wall perpendicular to the heat flow direction, k is the thermal conductivity of the wall assembly, T_A and T_B are the air temperatures of the interior and exterior environment across the wall having h_1 and h_2 as the convective heat transfer coefficients respectively.

Further rearranging the equation 1 yields

$$Q = \frac{(T_A - T_1)}{\frac{1}{h_1 A}} = \frac{(T_1 - T_2)}{\frac{L}{kA}} = \frac{(T_2 - T_B)}{\frac{1}{h_2 A}} \qquad (2)$$

$$= \frac{(T_A - T_1)}{R_{\text{Conv, 1}}} = \frac{(T_1 - T_2)}{R_{\text{Wall}}} = \frac{(T_2 - T_B)}{R_{\text{Conv, 2}}} \qquad (3)$$

The Addition of numerators and denominators will yield

$$Q = \frac{(T_A - T_B)}{R_{\text{total}}} \qquad (4)$$

Where;

$$R_{total} = R_{Conv,1} + R_{Wall} + R_{Conv,2} \qquad (5)$$

Where R_{total} (°C/W) is total thermal resistance between the heat transfer mediums

Also, sometimes heat transfer across a medium is expressed in an analogous manner to Newton's law of cooling given as;

$$Q = UA\,\Delta T \qquad (6)$$

Comparing equation 4 & 5 yields

$$UA = \frac{1}{R_{\text{total}}} \qquad (7)$$

Where **U is the overall heat transfer coefficient**. Therefore, for unit surface area the overall heat transfer coefficient or thermal transmittance or U-value is equal to the inverse of the total thermal resistance.

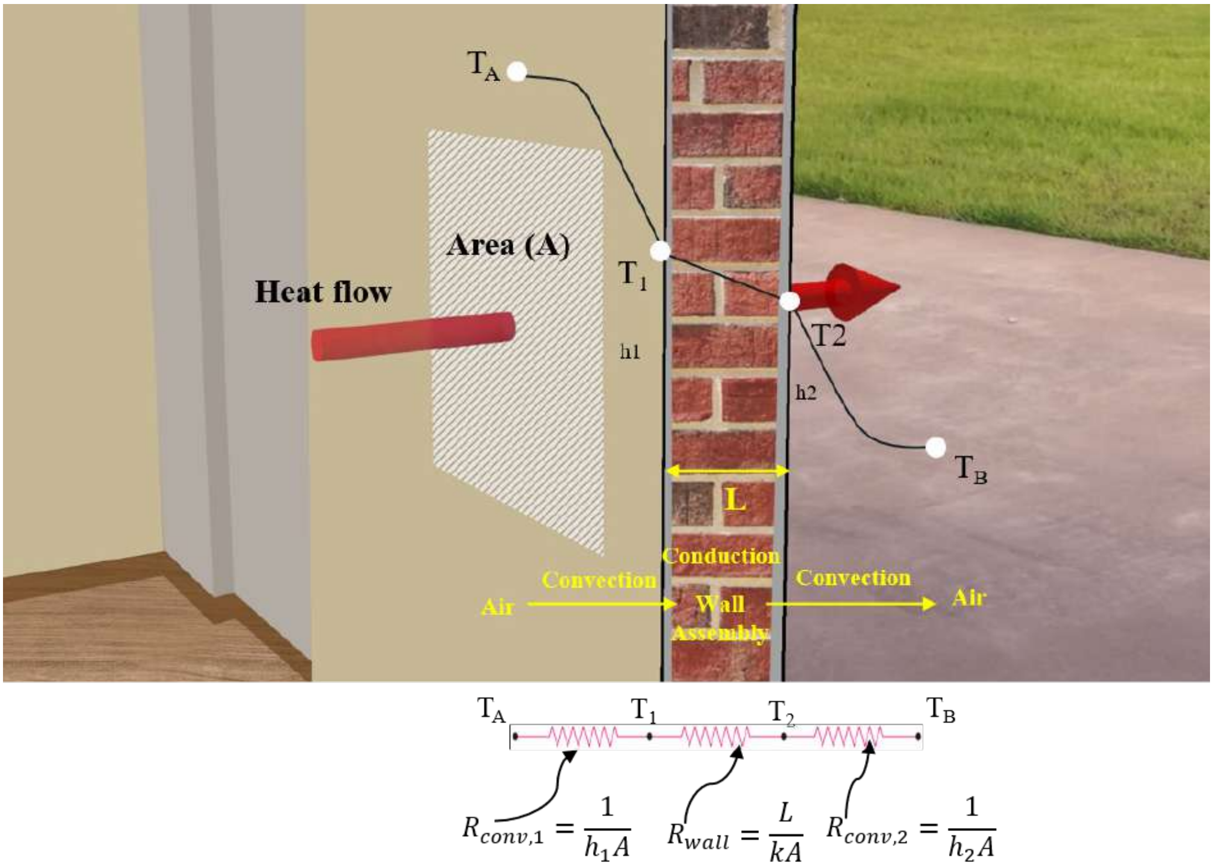


Figure 17: The heat flow and thermal resistance network across a plane wall subjected to convection on both sides

» ***Lower the U-value of a material, the lesser the heat transfer and better the thermal performance of the envelope.***

19 and *20* present the U-values of various wall and roof assemblies being used in the affordable housing sector of the country.

Insulating the roof and walls is done to reduce the overall U-value. Due to their low thermal conductivity, insulating materials can significantly resist heat gain in warm/hot climate and can resist heat loss in a similar way in cold climate. Any insulation or building material's resistance to conductive heat flow is measured or rated in terms of its 'Thermal Resistance' or R-value. Controlling heat flow is one amongst the other performance requirements of the building envelope. Thermal resistance refers to a barrier to heat flow across the specimen. The higher the thermal resistance, the lower will be the heat transfer to and from the building envelope.

» ***Higher the R-value, greater is the insulating effectiveness of the material.***

The R-value depends on the material's characteristics, its thickness, and thermal conductivity. The density of the material also affects its thermal conductivity.

Currently Expandable Polystyrene (EPS) and Polyurethane are being majorly used in the affordable housing sector of India [19].

Roof insulation: A large reduction in heat gains is possible for the top floor with roof insulation.

Wall insulation: Wall insulation works best in regions when the diurnal temperature range is high like in hot & dry climate or composite climate but not in the warm & humid climate.

In addition to walls and roof, windows also play a dominant role in regulating the building's indoor thermal comfort, aesthetics, daylighting and consequently overall energy consumption. Selection of window glass greatly affects the penetration of solar heat gain. For maximum solar heat gain, clear glazing should be selected, especially in cold climates. Where solar heat gain is not desired, as in the case of interior load dominated buildings, other types of glazing should be specified that minimize heat transfer through the glass. Spectrally selective glazing has the ability to screen for certain wavelengths of light.

Solar Heat Gain Coefficient (SHGC) value of glass: SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. Climate, orientation, and outdoor shading are the three important factors to be considered for determining the best SHGC rating for a particular location.

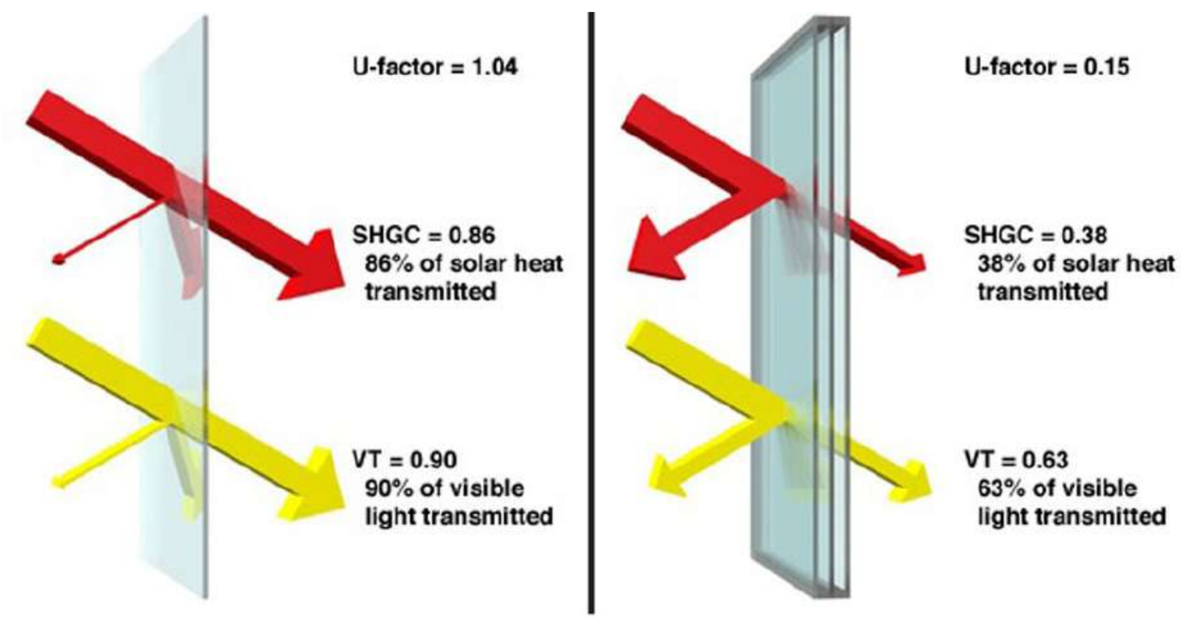


Figure 18: Comparison of Single-glazed and Triple-Glazed, Medium-solar-gain Low-E Glass

(Source: https://hscorp.ca/resources/a-window-into-energy-efficiency/)

» ***A product with a high SHGC rating is more effective at collecting solar heat during the winter.***

» ***A product with a low SHGC rating is more effective at reducing cooling loads during the summer by blocking heat gain from the sun.***

Low SHGC is desirable in cooling dominated regions

Table 4: Prescribed envelope characteristics in different climatic zones

CLIMATE ZONE	BUILDING ENVELOPE COMPONENT [20]					Minimum Openable Window to Floor Area ratio (WFR_{op}) [21]
	Wall	Roof	Glazing			
	U value (W/m²K)	U value (W/m²K)	U value (W/m²K)	SHGC (W/m2K)		
				WWR<20%	WWR>20%	
Hot & Dry	≤2.5	≤1.2	≤5.7	≤0.5	≤0.42	10%
Warm & Humid	≤2.5	≤1.8	≤5.7	≤0.5	≤0.42	16.66%
Composite	≤2.5	≤1.2	≤5.7	≤0.5	≤0.42	12.5%
Temperate	≤1.1	≤1.2	≤5.7	≤0.6	≤0.48	12.5%
Cold	≤2.5	≤1.2	≤5.7	≤0.8	≤0.80	8.33%

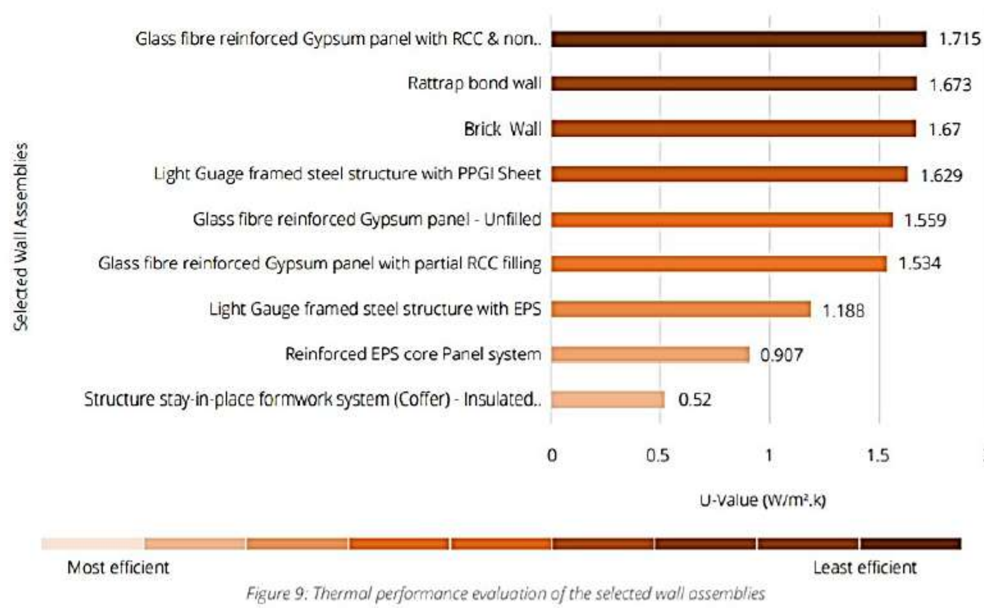


Figure 19: Thermal performance evaluation of selected wall assemblies [22]

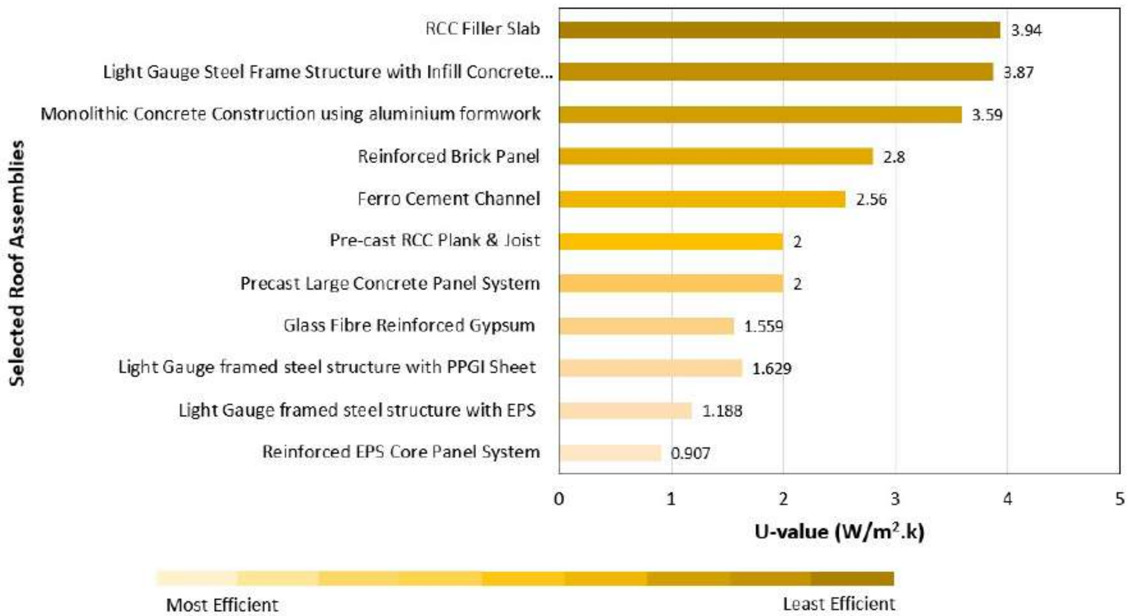


Figure 20: Thermal performance evaluation of selected roof assemblies [19] [23]

Air tightness

Airtightness is the fundamental building property that impacts infiltration and exfiltration through cracks, interstices or other unintentional openings of a building, caused by pressure effects of the wind and/or stack effect. The air leakage through building materials and components may happen due to expansion or contraction subjected to the varying degrees, depending on seasonal and diurnal exterior ambient air temperatures. Fluctuations in the ambient air temperatures can alter the sealing characteristics of windows, curtain walls, and doors by changing weather seal compression ratios. Thermal expansion or contraction of framing materials coupled with thermal blowing due to temperature gradients through the product, and alterations in the effective leakage areas due to weather seal shrinkage and compression set, can also significantly alter the air leakage rates of these products in field service applications.

» ***Higher thermal resistance and maximum air tightness is recommended for conditioned buildings of warm & humid and temperate climate [24].***

Surface color

Surface color determines how much of solar radiation is absorbed by the building envelope. The proper choice of material absorption has a great influence on the reduction of temperatures and energy requirements of the building.

» ***Lighter surface color of building envelope is recommended for cooling dominated regions to facilitate minimum heat gain.***

Insulating paint with its nanoparticles has a considerable impact on the reduction of temperature.

» ***Dark surface colors are recommended for heating dominated regions to maximize heat gain.***

4.4 Natural ventilation & openings

Natural ventilation is the process of pulling fresh air into a building from the outside. It does not involve any complex high energy consuming mechanical system and achieve through a passive design. For indoor air movement, naturally ventilated buildings mostly rely on building openings including doors, windows, ventilators etc. and at most use small ceiling fans. Whenever the conditions are favorable, the building should be designed to take the advantage of natural ventilation strategy. Wind-based ventilation (also known as cross ventilation) or Buoyancy-driven ventilation (also known as stack-effect ventilation) are two main kinds of ventilation that occur naturally in buildings. The ventilation strategies for enhancing indoor air flow through natural ventilation are:

4.4.1 Building Orientation:

A wind incidence at 45 degrees would increase the average indoor air velocity and would provide a better distribution of indoor air movement. Figure 21 (a) shows the outline of air flow at 90° and Figure 21 (b) at 45°, to a building square in plan. In the second case a greater velocity is created along the windward faces, therefore the wind shadow will be much broader, the negative pressure (the suction effect) will be increased and an increased indoor air flow will result.

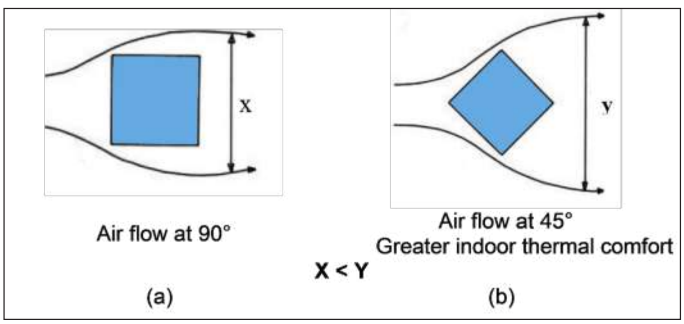


Figure 21: Building orientation for enhanced ventilation

4.4.2 External Features

External features of the building can redirect the prevailing winds to cross-ventilation. For example, if the air flow is at 45° to an elevation, a projecting wing of an L-shaped building can more than double the positive pressure created. A similar funnelling effect can be created by upward projecting eaves as shown in the below Figure.

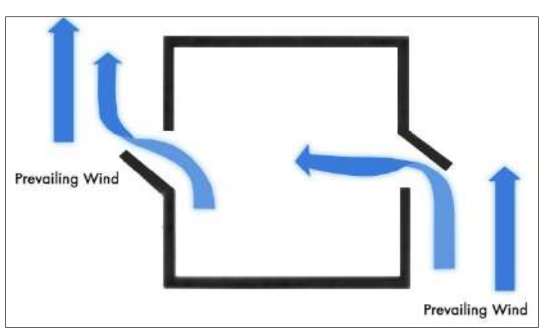


Figure 22: Funneling effect for enhanced natural ventilation

4.4.3 Cross-ventilation

Windows or ventilation openings placed on opposite sides of the building give natural breezes a pathway through the structure. This is called cross-ventilation.

Placing openings across from, but not directly opposite, to each other causes the room's air to mix, better distributing the cooling and fresh air.

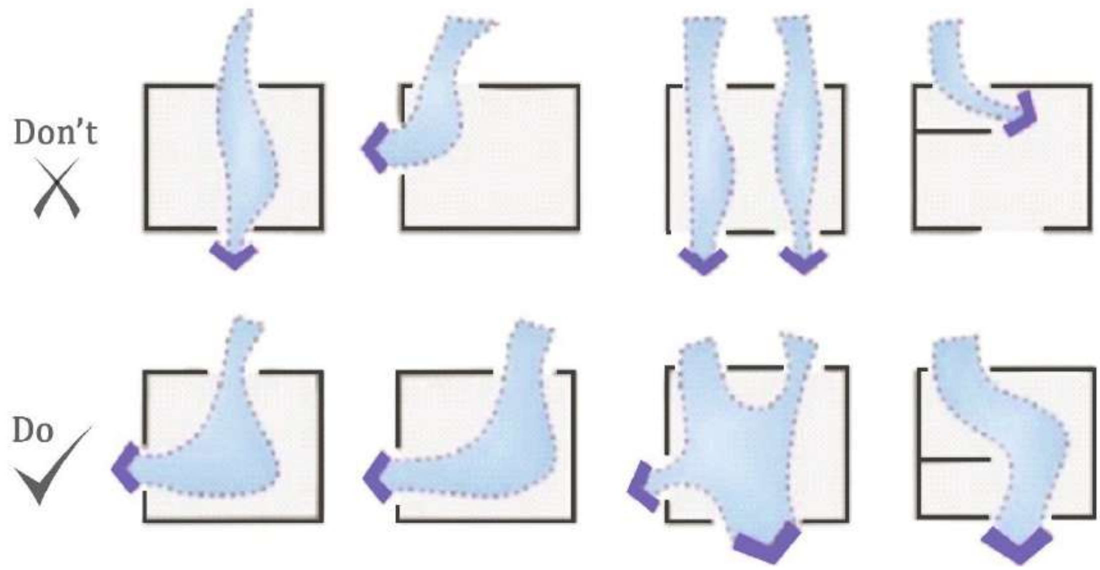


Figure 23: Dos and Don'ts for correct window placement (Figure amended from National Building Code of India [12])

4.4.4 Position of openings

To be effective, the air movement must be directed at the body surface. This means that air movement must be ensured through the space mostly used by the occupants i.e., through the 'living zone' (up to 2 m high). As shown in 24 below, if the opening at the inlet side is at a high level, regardless of the outlet opening position, the air flow will take place near the ceiling and not in the living zone.

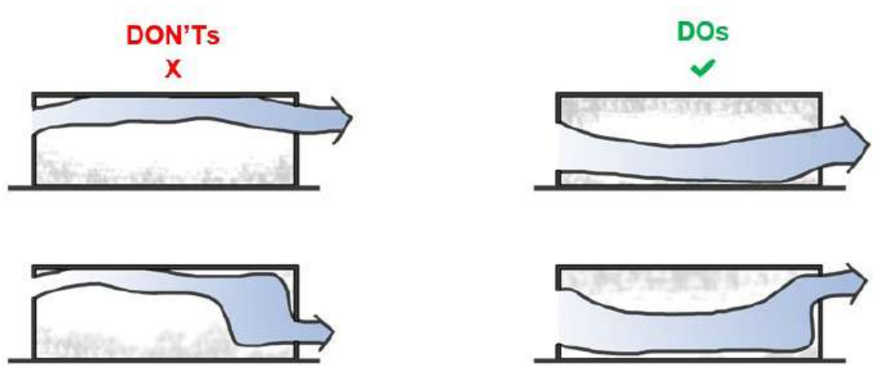
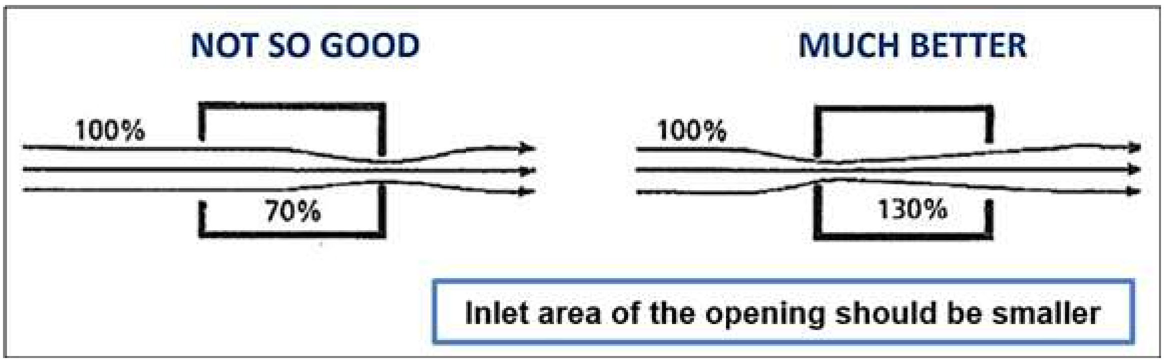


Figure 24: Dos and Don'ts for correct window placement (Modified from [25])

4.4.5 Size of openings

For an adequate amount of air, the area of operable windows or louvers should be 20% or more of the floor area, with the area of inlet openings roughly matching the area of outlets. If the areas of inlet and outlet openings should not be kept same and the inlet opening must be smaller. In doing so, the purposeful creation of positive and negative air pressure zones can create an increased air flow through a building or across a surface creating a cooling effect. This effect is also known as Venturi effect.

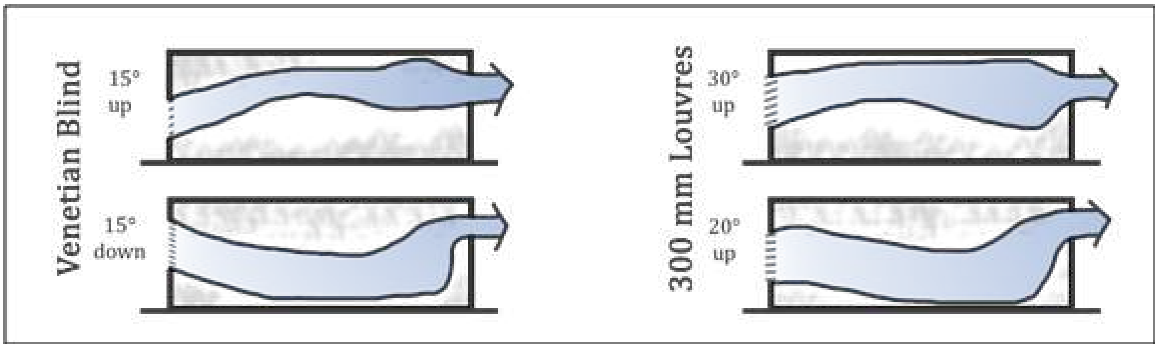


4.4.6 Control of openings

Sashes, canopies, louvres and other elements controlling the openings, also influence the indoor air flow pattern in the following manner.

Sashes can divert the air flow upwards. Only a casement or reversible pivot sash will channel it downwards into the living zone.

Canopies can eliminate the effect of pressure build-up above the window, thus the pressure below the window will direct the air flow upwards. A gap left between the building face and the canopy would ensure a downward pressure, thus a flow directed into the living zone.



Louvres and shading devices may also present a problem. The position of blades in a slightly upward position would still channel the flow into the living zone (up to 20° upwards from the horizontal).

4.4.7 Stack Ventilation

Stack effect works on the principle of convection which causes warm air to rise and draw in cool air. The warm air which rises due to increased buoyancy escapes the building through high level outlets, drawing in lower-level cool night air or cooler daytime air from shaded external areas or evaporative cooling ponds and fountains.

Stack ventilation is driven by the negative pressure generated as the cooler air from the outside rushes inside the building and exhausts at a high level through the stack opening. Since the negative pressure decreases with the height of the building the lower floors exhibit higher negative pressure compared to the higher floors.

Correct placement of the stack exhaust and adequate sizing of the stack exhaust opening are vital for harnessing the maximum advantage of stack ventilation.

CASE STUDY 1: Smart Ghar III, Rajkot (Source: BEE1i.pdf (gkspl.in))

Even though Rajkot has good wind speed, the design and layout of buildings are such that the wind does not reach all the flats. Often there are instances when there is low or no wind flow. A provision has been made to ensure adequate ventilation (10 air change rate) through all flats, by using the existing service shaft between two flats. This assisted ventilation concept will have a roof feature and a fan on top of the shaft, which will create negative pressure in the shaft (with / without ambient wind) improving air-change through the flats.

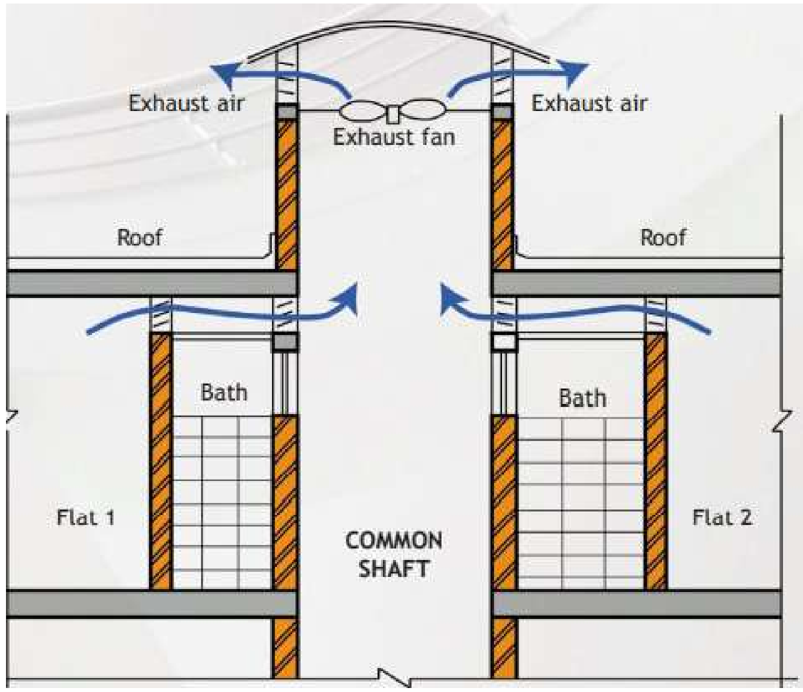


Figure 25: Conceptual sketch of assisted ventilation through the common shaft between the flats

This is to ensure that the top floors of the multistorey building are able to reap the benefit of the stack ventilation and the warm air rising upwards exit only from the stack exhaust opening without entering the top most floor.

Normally, stack exit must be one floor higher than the top floor.

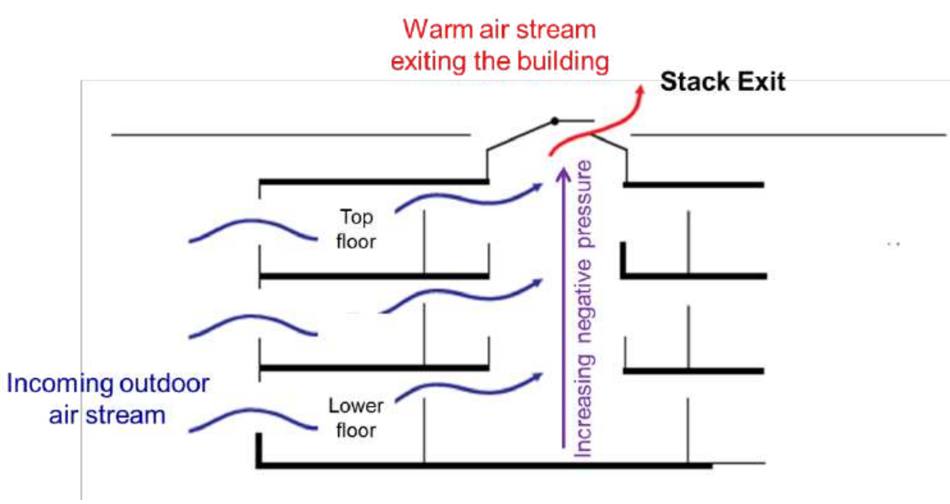


Figure 26: Stack ventilation

4.5 Shading

In cooling dominated regions, radiant heat from the sun passes through glass windows and is absorbed by building elements and furnishings, which is then re-radiated inside the dwelling. The re-radiated heat has a longer wavelength and cannot pass back out through the glass as easily. This 'trapping' of radiant heat must be avoided in summer. Thus, shading of a building and its outdoor spaces is important to reduce summer heat gain, improve thermal comfort and save energy. The air-conditioned buildings need full protection from solar heat through window. For non-air-conditioned buildings, this requirement can be fulfilled by proper orientation and selection of suitable shading devices.

Shading devices used can be generally classified into three groups:

1. **External shading,** such as louvers, sun breakers, vegetation (trees, plants etc.), verandahs, etc.;
2. **Internal shading,** like curtain, Venetian blind, etc.; and
3. **Advanced solutions,** like automated shading, dynamic solar shading systems, heat absorbing or heat reflecting glass, tinted glass, etc.
4. Shading requirements vary according to climate and house orientation
5. **North-facing openings (and south-facing ones above the tropic of Capricorn)** receive higher angle sun in summer and therefore require narrower overhead shading devices than east or west-facing openings. Examples include fixed horizontal shading devices such as eaves, awnings, and pergolas with louvres set to the correct angle.

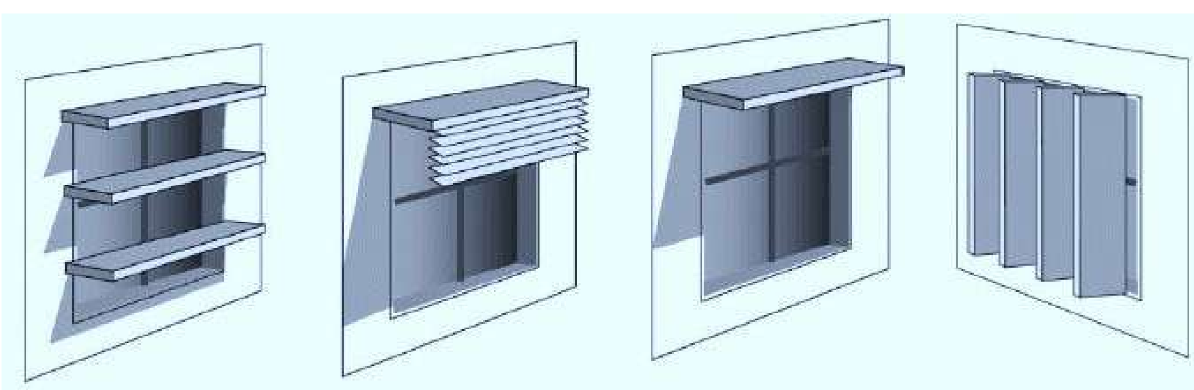


Figure 27: Fixed horizontal shading devices

East and west-facing openings require a different approach, as low angle morning and afternoon summer sun from these directions is more difficult to shade. The area of glazing on the east and west orientations should be kept to a minimum where possible, still allowing for good cross-ventilation. Adjustable shading devices, such as external blinds, is the optimum solution for these elevations.

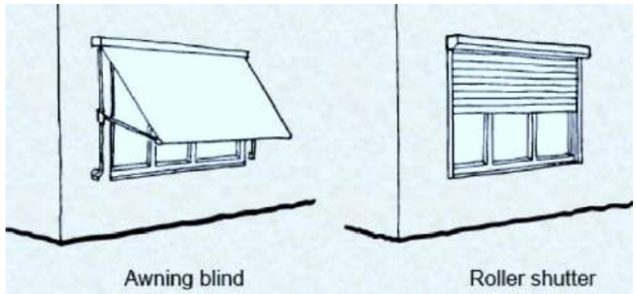


Figure 28: Adjustable shading devices

Plantings, deciduous vines, shade cloth and screens can all be used in conjunction with pergolas to provide seasonal shading.

Shade Cloth	Combining pergolas with vegetation
	

Vegetative Cooling

Horizontal shading v/s Vertical Shading

» Vertical shading device protects from sun on the east and west side elevation.

» Horizontal shading device protects from sun at high angles and opposite to the wall to be shaded such as north and south sides.

The combination of horizontal and vertical shading device protects from sun in all directions.

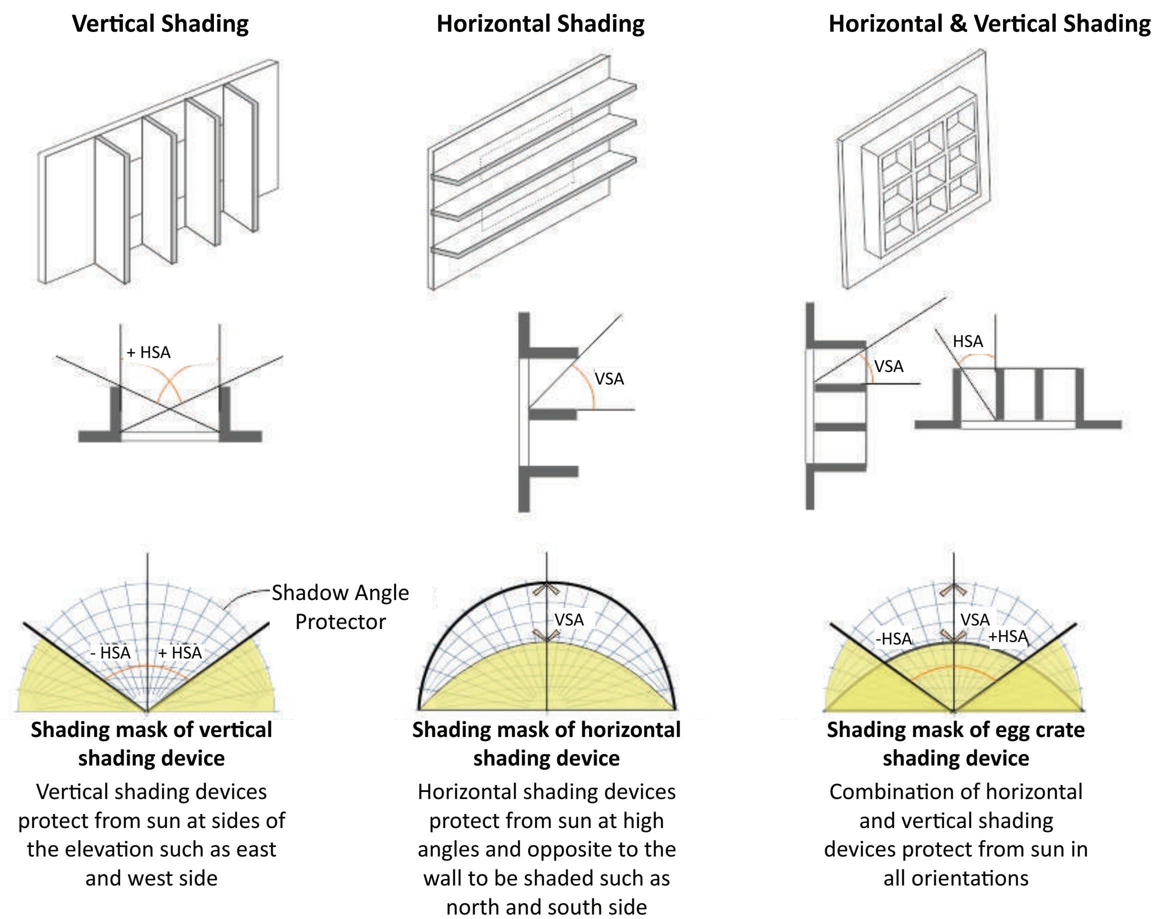


Figure 29: Horizontal Shading v/s Vertical Shading

However, in all orientations, horizontal shading is more effective than a vertical shading because vertical shading fails to cover the whole length of façade, reduces daylight penetration and restricts the extent of external view.

Some climate specific shading responses for passive cooling:

Warm and humid climate	Hot and Dry Climate	Composite Climate
» Essential to shade all external openings and walls year round » highly advantageous to shade the whole roof. » Perforated facades are recommended for warm & humid regions to avoid overheating and address humidity problem. » A 'fly roof' can be used to shade the entire building. It protects the core building from radiant heat and allows cooling breezes to flow beneath it.	» Use adjustable shade screens or deep overhangs (or a combination of both) to the east and west. » Deep covered balconies, verandas or shaded courtyard should be placed next to the main living areas to act as a cool air well. » Tall, narrow, generously planted courtyards are most effective when positioned in a way that they are shaded by the house.	» Provide passive solar shading to all north-facing openings, using shade structures or correctly sized eaves. » Use adjustable shade screens or deep overhangs to the east and west. It can exclude low angle sun very effectively.

4.6 Evaporative cooling

Evaporative cooling is used to produce indoor comfort in buildings by utilizing water as a heat sink. The sensible heat transfer to latent heat produces cooling effect due to evaporation of water and thus results in the drop of the ambient temperature. Evaporative cooling process is simple and in-expensive, applicable for low to medium humidity areas and is dependent on the wet-bulb depression of the ambient air.

Vetiver Shades are cost effective and aesthetic. They could be rolled up when not in use. When in use, they could be sprayed with water to increase the humidity and cool down the hot air. Doubles up as internal shading device. (Source: India Vetiver Crafts)

Passive Downdraft Evaporative Cooling

Torrent Research Centre, Ahemdabad [26]

Beehive-inspired zero electricity air conditioner (Source: Ant Studio, New Delhi, India)

4.7 Insulation

The thermal comfort in a building at low energy cost can be achieved by adopting an energy efficient building design by incorporating the use of low energy adequate thermal insulation materials in combination with other building materials while making the building envelope. Depending upon the thermal conductivity value of the building material, they offer thermal resistance to conduction of heat. However, compared to several building materials commonly used in construction, such as brick, Fly-ash brick, having a thermal conductivity of 0.5 to 0.7 W/m°K, the thermal conductivity of insulation materials is remarkably low, often less than 0.06 W/m°K.

Insulating materials, due to their low thermal conductivity, can substantially resist transfer of heat from the exterior to the interiors of the building if external temperature is high, and resist heat transfer from interiors to the exterior in a similar way when the external temperature is low.

Effect of Thermal Insulation: Any insulation or building material's resistance to conductive heat flow is measured or rated in terms of its 'Thermal Resistance' or R-value.

Higher the R-value, greater is the insulating effectiveness of the material.

The R-value depends on the material's characteristics, its thickness, and thermal conductivity. The density of the material also affects its thermal conductivity.

As insulation material having low thermal conductivity and large thickness can offer higher thermal resistance (R-value) to heat flow. This factor plays a major role in reducing conduction of heat in buildings.

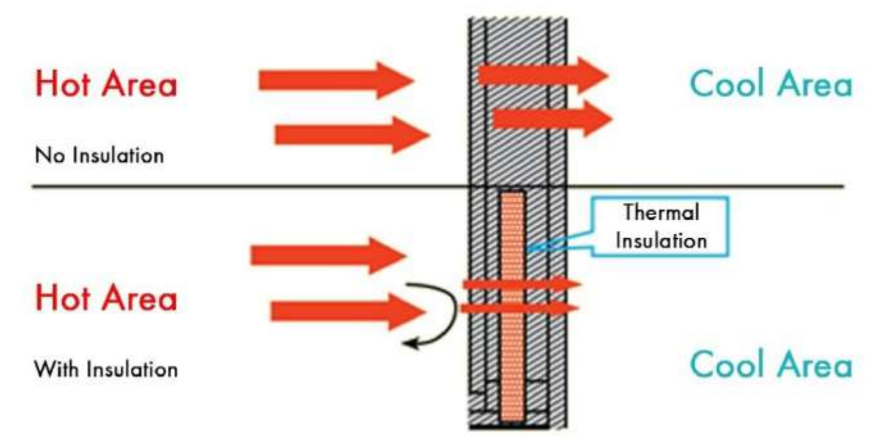


Figure 30: Working of insulation through wall section

- Heat always flows from high temperature to low temperature
- Insulation materials do not transfer heat well thus reduce the heat transfer

Effect of Wall Insulation: The external wall insulation system generally comprises of an insulation layer, a waterproofing or protective layer along the thermal mass, exterior or interior.

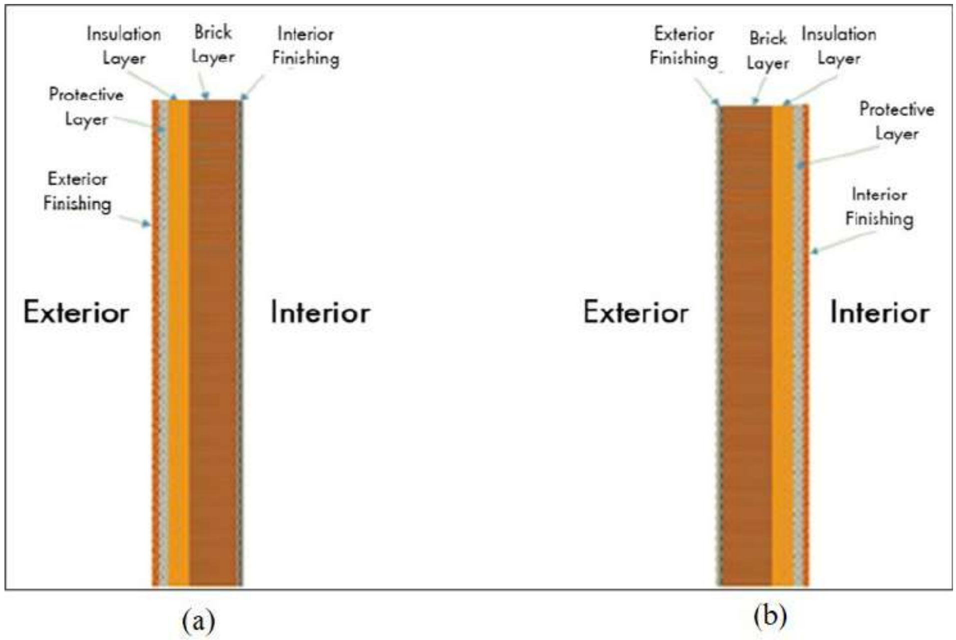


Figure 31: Effect of wall insulation: (a) exterior wall insulation, (b) Interior wall insulation

Effect of Roof Insulation: Roofs receive a large amount of heat gain, thus, insulation layer becomes an important aspecct in the roofing system (insulation + waterproofing) to achieve cools in summer, warms in winter and thereby save energy.

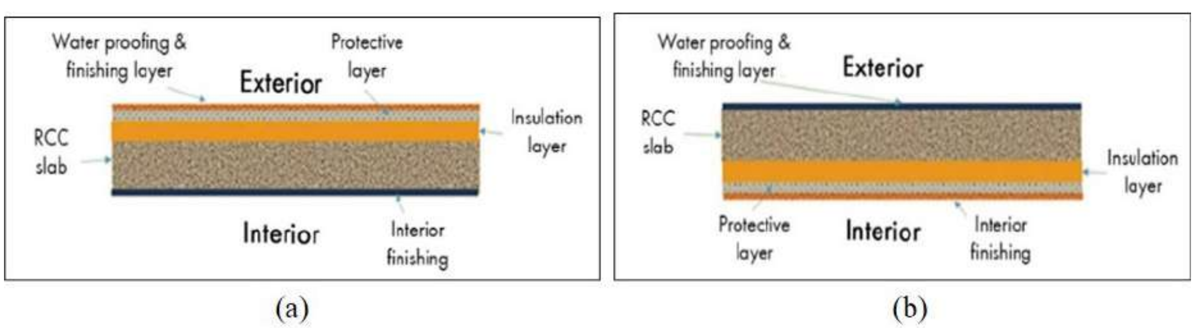


Figure 32: Effect of Roof Insulation: (a) Roof with over-deck insulation, (b) Roof with under-deck insulation

Effect of Cavity Wall Insulation: Cavity wall insulation brings additional benefits in composite or hot climates by reducing carbon emissions, heat transfer, and improving health and indoor comfort.

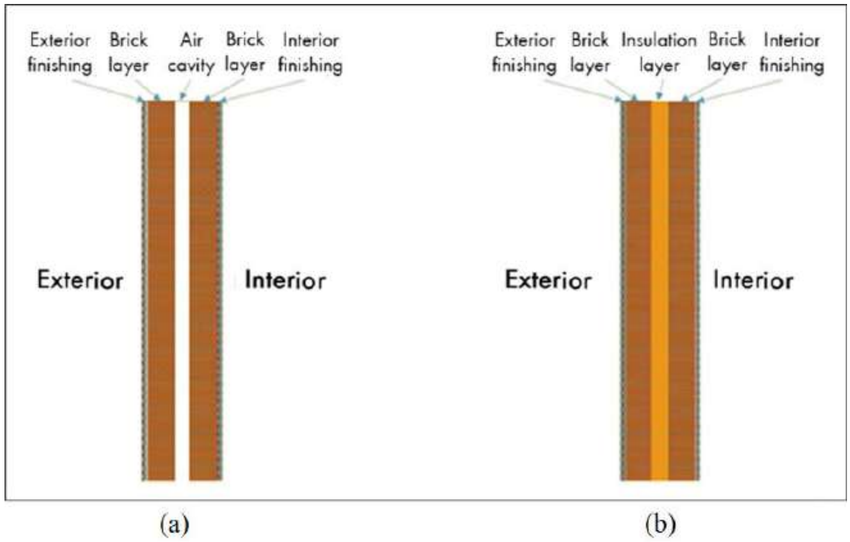
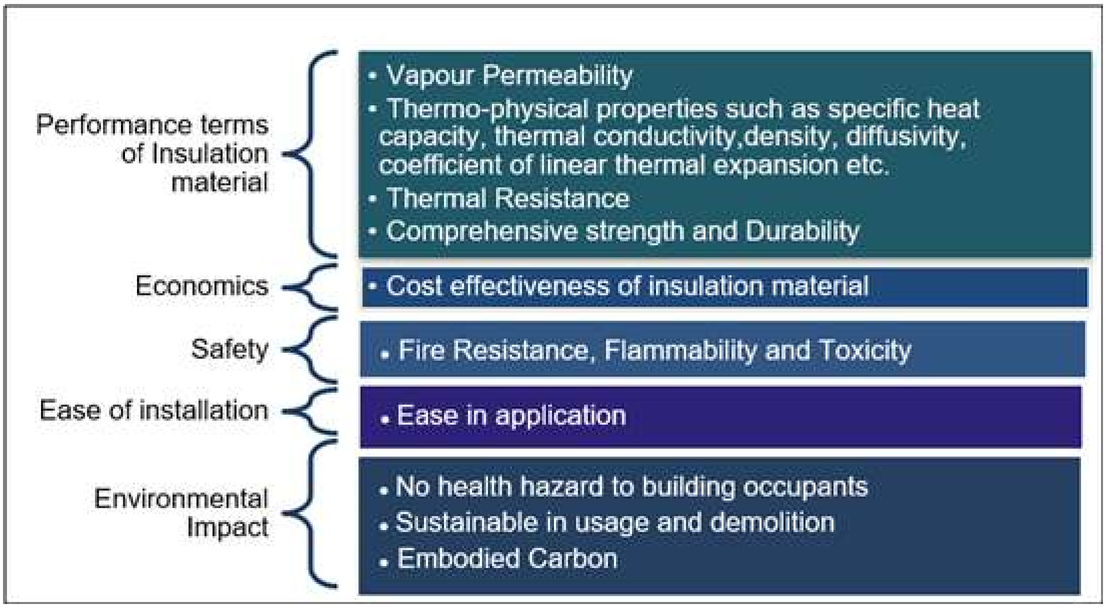


Figure 33: Effect of cavity wall insulation: (a) Cavity wall without insulation, (b) Cavity wall with insulation

Table 5: Prescribed minimum R-values and maximum U-factors for roof and walls [27][28]

Envelope	Climate Zone	24 hours Buildings		Daytime and other types Buildings	
		Max. U-factor W/m2.K	Min. R-value of insulation alone m2.K/W	Max. U-factor W/m2.K	Min. R-value of insulation alone m2.K/W
Roofs	Composite	0.261	3.5	0.409	2.10
	Hot & Dry	0.261	3.5	0.409	2.10
	Warm & Humid	0.261	3.5	0.409	2.10
	Moderate	0.409	2.1	0.409	2.10
	Cold	0.261	3.5	0.409	2.10
Walls	Composite	0.440	2.1	0.440	2.10
	Hot & Dry	0.440	2.1	0.440	2.10
	Warm & Humid	0.440	2.1	0.440	2.10
	Moderate	0.440	2.1	0.440	2.10
	Cold	0.369	2.2	0.352	2.35

Key considerations for selection of insulation materials



Insulation in residential buildings is generally not taken as an individual component and rather should be considered with the design strategies. Some of the commonly used Insulation for housing projects are mentioned in the table below:

Table 6: Comparison of commonly used Insulation Materials [28]

Characteristic of insulating materials	Insulating Power	Density	Fire Resistance	Water vapor diffusion	Resistance to water	Compression Strength	Traction Strength	Heat Resistance	Absorption of vibrations	Absorption of aerial noise	Cost at given insulation	Embodied Energy
Light mineral Wool	+	_._	++	-	0	_._	_._	+		++	+	_._
Dense Mineral Wool	++	+	++	_._	0	0	_	++	++	+	+	0
Glass foam	+	+	++	++	++	++	++	++	_._	_	+++	0
PUR	++	-	0	-	0	+	+	++	_	_._	+	++
EPS	++	_._	+	+	0	+	+	0	_	_._	+++	_
XPS	++	0	+	++	+	+	++	0	-	_._	+	+
++ Very high; + High; 0 Average; - Low; _._ Very low												

Table 7: Insulation technology used in housing projects (data gathered by TERI research team under Sustainable Housing Leadership Consortium (SHLC))

Insulation Technology	Rate	Embodied Energy	Sustainability Feature	Replicability/ Scalability	Region Specific
Brick bat coba roofing	Rs. 120-340 / sq.ft	The construction can make use waste and broken brick bats	Provides insulation and hence better thermal comfort in spaces below the roof	Replicability and scalability of the technique depends on the availability of fired clay brick in the region	Applicable across all regions
Roof with insulation and cool roof	Rs. 125-250 / sq.ft	Data Unavailable	Polymer based insulation provide high energy savings by reducing heat ingress	Variety of insulation materials readily available across India	Applicable across all regions
Roof with reflective surface/cool roof	Rs. 15 / sq.ft. for cool finish (only for high reflective paint)	Data Unavailable	Reduces heat ingress from the roof, leading to a difference of 4-6 degree Celsius & indoor temperature	High SRI paints are readily available in the market these days	Applicable across all regions

Key Barriers in the adoption of thermal insulation:

» Poor awareness among the stakeholders and end users about the benefits of using different insulation products in the building

» Limited knowledge about monetary quantification of adopting thermal considering the uniqueness of each housing project, climate, location etc. in the most appropriate manner.

» Availability of expert services to beneficiaries is limited with regard to durability of the insulation products, potential energy savings, payback period on additional investment, etc.

» Poor documentation of standard procedures and correct preparations, actual success and failure stories in the public domain to instil confidence among the stakeholders regarding the application of thermal insulation.

» Inadequate independent/third-party testing facilities in the country to create

» awareness among building developers, designers, and other stakeholders about thermal characteristics of insulation products and other building construction materials.

4.8 Thermal Mass

The property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations is known as thermal mass. Scientifically, thermal mass is equivalent to volumetric heat capacity i.e., amount of heat to be supplied to a given mass of a material to produce a unit change in its temperature.

During warm weather conditions thermal mass can absorb heat gained from sunlight. This will make the interior space more comfortable, and greatly reduce the cooling demand and cost of air conditioning. During the night as a building cools the stored heat energy is then released into the building interior space reducing the heating demand. Thermal mass is most beneficial in climates where there is a large fluctuation between the daytime, and night time ambient temperatures. In areas with high night time temperatures thermal mass can still be utilized, the building must then be ventilated at night with the cooler night air to exhaust the stored heat energy.

Heat stored in an object can be calculated as :

$Q = m*C*\Delta T$

» Where, ***Q*** is the quantity of heat transferred to or from the object, m is the mass of the object, ***C*** is the specific heat capacity of the material the object is composed of, and Δ***T*** is the resulting temperature change of the object.

Table 8: Properties of common wall materials for thermal mass calculations [27]

Type of Material	Density (kg/m³)	Thermal Conductivity (W/m.K)	Specific Heat (kJ/kg.K)	Volumetric Heat Capacity (kJ/m³.K)
Dense Concrete	2410	1.740	0.88	2100
RCC	2288	1.580	0.88	200
Solid Burnt Clay Brick	1920	0.81-0.98	0.80	1500
Fly ash brick	1520	0.631	0.99	1500
AAC block	642	0.184	0.79	500

Key Recommendations:

» The thermal mass with high density is more effective for passive solar material i.e., denser the material the better it stores and releases heat.

» Use thermal mass in climates with large diurnal temperature range and effectively locate and integrate with passive solar design, by considering the placement of added mass.

» Do not substitute thermal mass for insulation. It should be used in conjunction with insulation.

» For heating and cooling requirements, the ground floor is the most ideal place for thermal efficiency in winter and summer.

» The color of thermal mass and low reflectivity plays an important role as well. Dark, matt or textured surfaces absorb and re-radiate more energy than light, smooth, reflective surfaces.

Climate	Thermal Mass Placement & Design Guidelines
Hot & Dry	High thermal mass construction with high insulation levels: This is the most effective strategy to reduce heat gains and should be used with proper shading. In the hot dry climate, insulation should be on the external side with the high mass material on the inside protecting it from the summer sun.
Warm & Humid	High mass buildings with provision of a good ventilation system can achieve comfortable conditions in hot humid climate. By using thermal mass that is shaded during the day and is exposed to cooling breezes overnight, the natural cooling potential can be realized. Innovative well insulated and shaded thermal mass with water proofing designs have been able to lower night time temperatures by 3 to 4˚C in hot humid areas with modest diurnal ranges
Temperate	Increase thermal resistance and thermal capacity (time-lag) Since the temperatures are not very high throughout the year, high Insulation and low/moderate thermal mass will work for temperate climate. High thermal mass can be used in those areas where day temperatures are quite high.
Composite	Design guidelines for thermal mass placement in composite climate is similar to hot & dry climate. The temperatures are high in summer and lower in winter thus need high insulation and thermal mass to achieve better thermal comfort.

4.9 Cool Roofs

For qualifying as a cool roof, roofs with slopes less than 20° shall have an initial solar reflectance of no less than 0.60 and an initial emittance no less than 0.90 [27]. Cool roofs are able to maintain a temperature difference of 6-8°C between ambient and indoor air temperature by:

» Reflecting away a percentage of the visible, infrared and ultraviolet radiation from the sun. This reduces the heat gained by the building itself and is called high solar reflectance.

» Re-emitting the remaining heat retained by the building. This helps in the cooling the building quicker as compared to traditional materials and is called high thermal emittance.

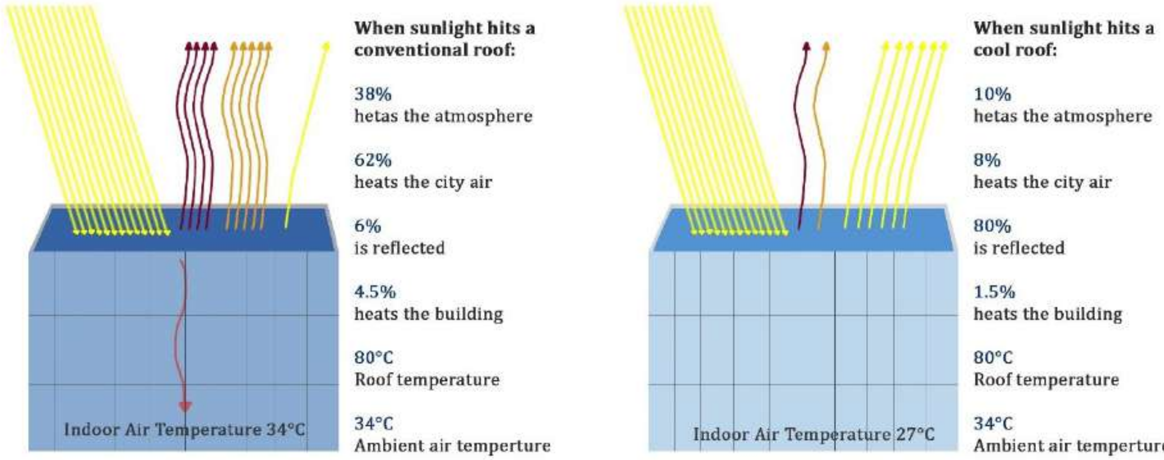


Figure 34: Conventional roof Vs Cool roof

Cool roofing can be achieved by one of the following ways:

4.9.1 Membrane cool roofs:

These roofs involve using pre-fabricated materials such as membranes or sheeting to cover an existing roof in order to increase the roof surface's SRI. These types of roofs can be polyvinyl chloride (PVC) or bitumen-based.

4.9.2 Tiled cool roofs:

These roofs involve the application of high albedo, china mosaic tiles or shingles on top of an existing roof or to a new roof.

4.9.3 Coated Cool roofs:

A roof can be made reflective by applying a solar reflective coating to its surface; such as lime wash, any acrylic polymer or plastic technology and are usually white in color.

4.9.4 Special cool roof materials such as ModRoof:

These roofs, made of coconut husk and paper waste, have been installed in households around Gujarat and Delhi and can serve as an alternative to RCC roofs. modular roofs provide greater cool roof benefits than regular roof materials and data collected from installed sites showed indoor air temperature being lower by 7-8°C (12.6 – 16.4°F), as compared to conventional concrete roofs in the hot & dry climate of Ahmedabad [29].

Figure 35: ModRoof installation in Ahmedabad by Mahila Housing SEWA Trust [29]

4.9.5 Green cool roofs

Green roofs provide a thermal mass layer which helps reduce the flow of heat into a building. The solar reflectance of green roofs varies depending on the plant types (generally 0.3-0.5). However, they are likely not a cost-effective solution for heat reduction in low-income communities in India.

Key Barriers in the adoption of cool roofs in Indian cities:

- Lack of awareness about the cool roof technological solutions, their benefits, maintenance issues, costs, correct application procedures etc.
- Lack of experience and expert work force for technology implementation
- Lack of incentives and policies for facilitating the adoption of technology at national, sub-national and local levels.
- Skepticism: The lack of a legislative framework results in owners and developers choosing roofs that minimize initial construction cost, rather than the aggregate cost of construction and lifetime energy consumption

Case Study: Pilot for cool roof implementation in a low income neighbourhood in Hyderabad [29]

Implementation: The pilot was undertaken by ASCI and IIIT-H in May and June 2017 to identify cost-effective cool roof solutions.

Pilot Size: Set of 25 low-income housing in Devarakonda Basti, Hyderabad. It comprised of primarily single-floor, dense residential homes, predominantly constructed of RCC and brick, with roofs made of corrugated asbestos sheets or concrete slabs

Material and cost: High-density Polyethylene (HDPE) cool roof coating membrane was used. It retails in Hyderabad for ₹13/square foot, but was provided by Dupont India for free.

Results:

- » Indoor air temperatures were lower by an average of 2°C were observed in the homes with cool roofs as compared to similar homes without cool roofs.
- » Peak over deck roof temperatures in the cool roof homes were observed to be 15°C lower than temperatures in homes with just asbestos roofs and 10°C lower than temperatures in homes with just cement roofs.

Figure 36: Cool roof pilot installation in Hyderabad [29]

5. Adaptive thermal comfort in Indian residences

So far energy efficiency policies for the building sector have focused largely making cooling and heating technologies more efficient energy-wise. But an adaptive thermal comfort standard can go much beyond this, opening up new opportunities that, while improving energy efficiency, improve thermal comfort as well. Adaptive thermal comfort approach states that people adapt through environmental interaction to changing conditions. Changes in the clothing pattern is a characteristic personal adaptation to changing ambient thermal environment changes. Other common adaptative actions include changing the activity, adjusting the openings, switching on fans, etc. Various field studies carried out in naturally ventilated and air-conditioned buildings of the country have demonstrated that wide comfort bandwidths exist for Indian subjects than the comfort bandwidths found for subjects residing in cold countries. This is due to higher degree of behavioural, physiological, and psychological adaptation to warm climates. Table 8 presents the excerpts from various thermal comfort field studies carried out in different climates of the country.

Table 9: Thermal comfort bandwidth in residential buildings located in cooling dominated regions of India

S.No	Work Title	City	Climate	Season	Building Type	Comfort band	Neutral Temperature	Indoor air speed
1	Adaptive use of natural ventilation for thermal comfort in Indian apartments [30]	Hyderabad	Composite	Summer and Monson	Residential	26-32.45°C	29.23°C	0.5m/s
2	Evaluation of data for developing an adaptive model of thermal comfort and preference [31]	Bhopal	Composite	Summer and winter	Residential and Commercial	20-30°C	-	-
3	Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings [32]	Kerla	Warm- humid	Summer and winter	Residential	23.5-32°C	-	0.5m/s

Table 9: Thermal comfort bandwidth in residential buildings located in cooling dominated regions of India

S.No	Work Title	City	Climate	Season	Building Type	Comfort band	Neutral Temperature	Indoor air speed
4	Thermal performance study and evaluation of comfort temperatures in vernacular buildings of north-east India [33]	Tezpur, Imphal and Cherrapunjee	Warm- humid and cold	Summer and winter	Residential	19-29°C	26°C	-
5	Adaptive comfort and thermal expectations- a subjective evaluation in hot humid climate	Chennai	Warm- humid	Summer and winter	Residential	26.8-31°C (TSI), 26-31.8°C (Tg)	28.8°C (TSI), 29°C (Tg)	1 m/s (Natural air flow), 2m/s (Fan forced air flow), >2.2 km/s (Discomfort)
6	Thermal comfort analysis of Indian subjects in multi-storeyed apartments: an adaptive approach in composite climate	Chandigarh and Roorkee	Composite	Summer, winter and monsoon	Residential	25.5-31.4°C	26.1°C	

Table 9: Thermal comfort bandwidth in residential buildings located in cooling dominated regions of India

S.No	Work Title	City	Climate	Season	Building Type	Comfort band	Neutral Temperature	Indoor air speed
7	Thermal comfort assessment and characteristics of occupant's behaviour in NV buildings in composite climate of India [34]	Jaipur	Composite	Summer and winter	Residential	25.2-30.6°C	27.9°C	0.27-0.62 m/s
8	An adaptive approach to define thermal comfort zones on psychrometric chart for naturally ventilated buildings in composite climate of India [35]	Jaipur	Composite	Summer and winter	Residential	18-32°C		0-0.2 m/s (Still air)
						Upto 33°C		0-0.5 m/s (Natural air flow)
						Upto 35°C		0-1.5 m/s (Fan forced air flow)

Thermal adaptation plays crucial role in energy efficient operation of building without compromising with human thermal comfort. Elevated air velocity is commonly desired to restore comfort requirements at higher temperatures especially in NV and MM buildings located in tropical countries like India. A thermal comfort field study conducted over a period of six years (2011-17) during summer and moderate seasons in composite climate of Jaipur (India) studied comfort conditions of a total of 4872 responses (1874 from NV buildings and 2998 from MM buildings). Subjects' responses and concurrent field measurements were utilized to investigate the impact of elevated air velocity on indoor thermal comfort [36]preferences and local adaptation. The graphical quantification of air velocity required to offset increased temperature was done following the similar approach as presented in ISO Standard 7730. A redefined air velocity offset chart for Indian subjects working in office buildings was proposed using the evidences (i.e., comfort expectations, preferences and local adaptation) collected from actual field observations. As presented in Figure 37, the offset in comfort operative temperature from base value of 28.04°C and 26.93°C for NV and MM buildings were obtained to be 4.78°C and 4.24°C, respectively for the elevated air velocity of 1.5 m/s.

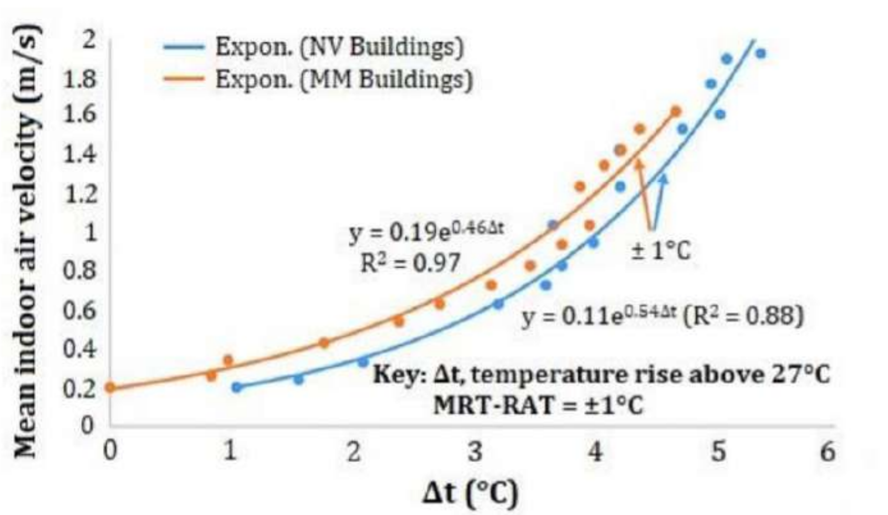


Figure 37: Elevated air velocity required to offset increased temperature in surveyed buildings [36]

Conclusions

A thermal comfort prescription has been developed to recommend the best design practices for achieving indoor thermal comfort for cooling dominated regions of the country which majorly include the four climatic zones (Hot & Dry, Warm & Humid, Composite and Temperate). This prescription also suggests the best passive strategies for maximizing indoor thermal comfort in these climatic zones. Literature review and detailed case studies helped in identifying and assessing the impact of key building design features incorporated in various cooling dominated regions of India since traditional times to modern current practices to achieve and maintain the thermal comfort. Moreover, this prescription guidebook throughs light upon the most widely accepted codes and standards describing the scope of applicability and limitations for Indian real estate sector to maintain the thermally comfortable interiors. Study reveals that, so far energy efficiency policies for the building sector have focused largely making cooling and heating technologies more efficient energy-wise. But an adaptive thermal comfort standard can go much beyond this, opening up new opportunities that, while improving energy efficiency, improve thermal comfort as well. Various field studies carried out in naturally ventilated and air-conditioned buildings of the country have demonstrated that wide comfort bandwidths exist for Indian subjects than the comfort bandwidths found for subjects residing in cold countries. This is due to the higher degree of behavioural, physiological, and psychological adaptation to warm climates. The current study helped in exploring and examining (through literature and case studies) the key design features, practices, codes and standards, and thermal adaptation characteristics playing crucial role and influencing the human thermal comfort. Embedding thermal comfort considerations right from pre design stage to post occupancy stage is required. Appropriate climatic analysis for identifying climate appropriate strategies can Maximize comfort. Also, the consideration of future climate change scenarios in designing new buildings which are ought to stay for next 20-25 Years may be a step towards creating comfortable and resilience-built environments for future. Since the building occupants play an active role in ensuring thermal comfort, the designers should follow the adaptive thermal comfort principles while designing buildings and cooling systems. The behavioural and psychological attitudes towards adaptive thermal comfort practices to reduce cooling requirements and promote a healthy living/working environment requires special focus.

Way Forward

» In line with the country's National Cooling Policy, there are hardly any states and city level initiatives for the wider application of innovative cool roof technologies and heat reflective solutions. Supporting focused evidence-based research is essential to mainstream these solutions and maximize the ground implementation.

» The implementation of the adaptive comfort approach in the comfort standards is usually restricted to the assessment of the summer season performance of naturally ventilated and unconditioned buildings, in particular concerning the design phase and service phase. Admitting the fact that adaptation takes place also in conditioned buildings provided with perceived adaptive opportunity, however it looks reasonable to extend the adaptive approach to all kinds of buildings.

» Various researchers have produced Adaptive comfort models for different climates and building types. Adaptive comfort models have matured as a theoretical research outcome but their practical implementation in building operation has yet to find its way. The primary reason for this is unique microclimate and operation characteristics associated with each building type and thus generalization of adaptive equation becomes a challenge in actual practice. Further there are still limited field studies conducted in buildings with low energy and passive strategies. Evidence-based research on the quantification of best comfort strategies for the design and operation of mixed-mode buildings is needed.

» More research on harnessing behaviour changes for promoting greater adoption of adaptive thermal comfort based cooling system operation, use of controls such as fans, windows, doors etc.is required. In addition, the end users must be educated about the adaptive comfort opportunities for maximizing their thermal comfort. This may include awareness about modulating their activity levels, opting for the right season specific clothing, best combination of using building environmental controls for their benefit etc.

» PCM based cool roof systems and heat reflective solutions are the upcoming technological interventions for addressing various concerns related to energy use, urban heat island effect and thermal discomfort. The benefits concerning building energy efficiency; improving the thermal comfort and energy saving have not been rigorously quantified in the context of Indian residential buildings in different climatic conditions. Therefore, evidence-based research is essential to mainstream these solutions and maximize the ground implementation

» There is a need to study the proposed technologies considering different aspects such as investigating different variants of PCM based cool roof and high reflective solution, influential position within the envelope, optimal quantity, method of incorporation and best passive/active strategy to be utilized feasibly to provide substantial information for their applicability.

» A promising solution to reduce the building energy consumption is to design low-energy buildings with synergy within architectural aspects, passive cooling technologies, and low energy cooling systems. These solutions include the integration of passive or low-energy strategies: natural and mechanical ventilation coupled with thermally activated building structures.

THERMAL COMFORT PRESCRIPTION FOR COOLING-DOMINATED REGIONS

Climate	Thermal Comfort & Daylight system : Resist heat gain / Promote heat loss	Common Building Design Strategies

Hot & Dry Climate

Increase thermal resistance
High Insulation

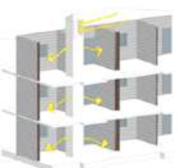
Increase thermal capacity (time-lag)
High Thermal Mass

Increase buffer spaces
Air locks / Balconies etc.

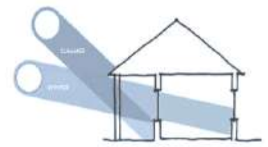
Compact internal planning
Openings for cross ventilation

Increase surface reflectivity
High SRI paints, Cool roofs, China mosaic tiles etc.

Increase air exchange rate (Ventilation during night-time)
Provide windows / Exhausts / Courtyards/ wind towers



Roof overhangs
Roof overhangs can shade from summer sun while letting in winter rays.



Increase humidity levels
Trees, water ponds, evaporative cooling, Potential heatsink, night cooling

Composite Climate

Increase thermal resistance
Moderate to High Insulation

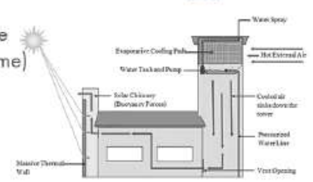
Increase thermal capacity (time-lag)
High Thermal Mass

Increase buffer spaces
Balconies, courtyards etc.

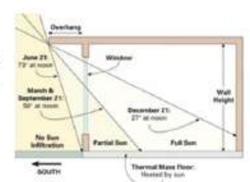
Compact internal planning
Openings for cross ventilation

Increase surface reflectivity
High SRI paints, Cool roofs, China mosaic tiles etc.

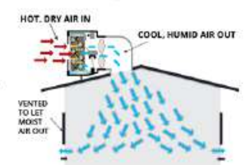
Increase air exchange rate (Ventilation during night-time)
Provide windows / Exhausts / Courtyards/ wind towers / solar chimney



Roof overhangs
Roof overhangs can shade from summer sun while letting in winter rays.

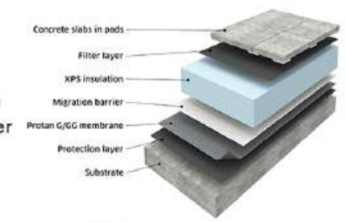


Increase humidity levels
Trees, water ponds, evaporative cooling, Potential heatsink



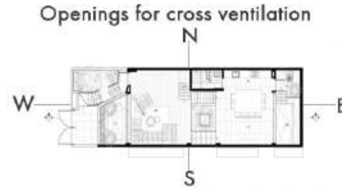
Warm & Humid Climate

Increase thermal resistance and thermal capacity (time-lag)
High Insulation & High thermal mass with water proofing

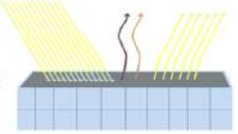


Increase buffer spaces
Balconies, verandahs etc.

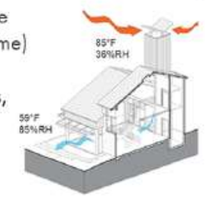
Elongated free plan can be evolved, if shaded well
Openings for cross ventilation



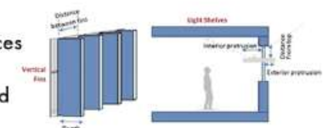
Increase surface reflectivity
High SRI paints, Cool roofs, China mosaic tiles etc.



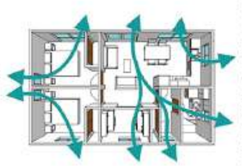
Increase air exchange rate (Ventilation during night-time)
Ventilated roof construction, Courtyards, wind towers (axial fans) and arrangement of openings



Shading
Walls, glass surfaces protected by overhangs, fins and trees

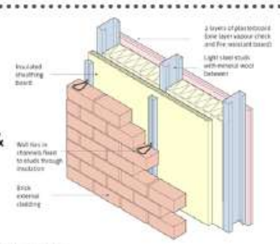


Decrease humidity levels
Dehumidifier/ desiccant cooling, Potential heatsink, Create Air pressure difference / Cross Ventilation enhancement



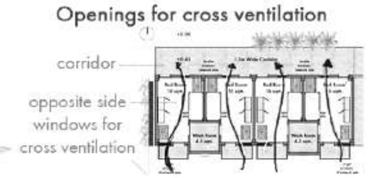
Moderate Climate

Increase thermal resistance and thermal capacity (time-lag)
High Insulation & low / moderate thermal mass

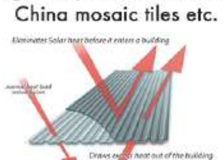


Increase buffer spaces
Balconies, verandahs, lobbies etc.

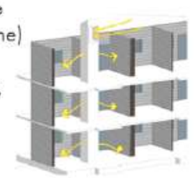
Elongated free plan can be evolved with single loaded corridor
Openings for cross ventilation



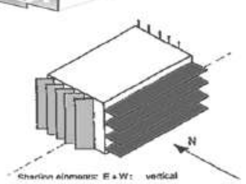
Increase surface reflectivity
High SRI paints, Cool roofs, China mosaic tiles etc.



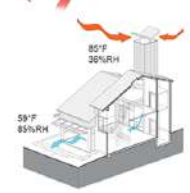
Increase air exchange rate (Ventilation during night-time)
Ventilated roof construction, Courtyards, wind towers (axial fans) and arrangement of openings



Shading
Walls, glass surfaces protected by overhangs, fins and trees

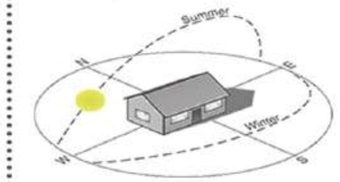


Decrease humidity levels
Dehumidifier/ desiccant cooling, Potential heatsink, Create Air pressure difference / Cross Ventilation enhancement

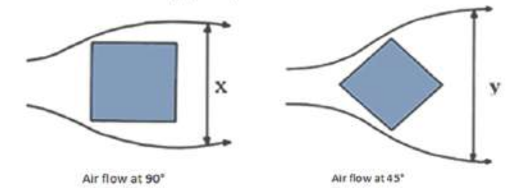


Common Building Design Strategies

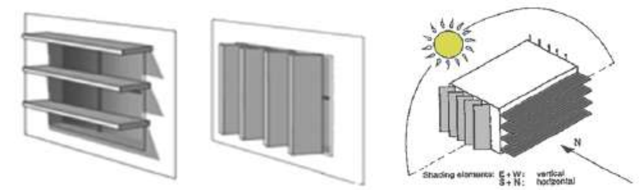
Decrease exposed surface Area
E-W longer axis; Low S/V ratio



Building orientation w.r.t Wind
A wind incidence at 45 would increase the average indoor air velocity (X<Y)



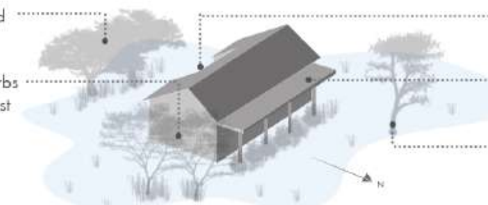
Increase Shading
Adjustable vertical shading on E-W facade & Deep horizontal shading / overhangs & trees on South & SW facade



Dense planting as wind breaks

Deciduous trees & shurbs shade the east and west wall & windows

Placement of Trees



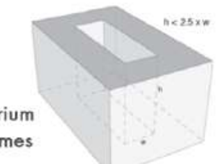
South facing courtyard with moist, cool fernery

Deciduous trees & vines to the north

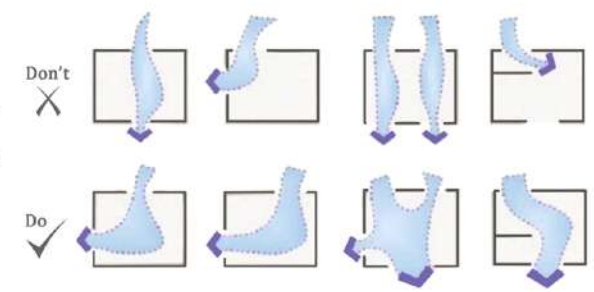
Keep evergreen trees well back from the

Window type
Taller windows give greater penetrations & broader windows give better distribution of light.

Atrium thumb Rule
To daylit all spaces bordering an interior atrium with diffuse daylight, the max. atrium height is about 2.5 times it's width.



Placement of windows
Larger windows on the windward side & smaller openings on leeward side. Air movement must be ensured through the space mostly used by the occupants i.e. through the 'living zone' (up to 2 m high).



CLIMATE ZONE	Building Envelope Component					Minimum Openable Window to Floor Area ratio (WFR_{op})
	Wall	Roof	Glazing			
	U value (W/m^2K)	U value (W/m^2K)	U value (W/m^2K)	SHGC (W/m^2K) WWR<20%	SHGC (W/m^2K) WWR>20%	
Hot & Dry	≤ 2.5	≤1.2	≤ 5.7	≤0.5	≤ 0.42	10%
Warm & Humid	≤ 2.5	≤1.8	≤ 5.7	≤0.5	≤ 0.42	16.66%
Composite	≤ 2.5	≤1.2	≤ 5.7	≤0.5	≤ 0.42	12.5%
Temperate	≤ 1.1	≤1.2	≤ 5.7	≤0.6	≤ 0.48	12.5%
Cold	≤ 2.5	≤1.2	≤ 5.7	≤0.8	≤ 0.80	8.33%

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The overall scope of the project includes standardization and measurement of building material, thermal and visual comfort study, development of performance standard matrices, guidelines and numerical toolkits and water

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The activities related to the sustainable use of water in habitats, includes both macro and micro level analysis in terms of water efficiency, conservation and management within a premise by end users in Indian cities. The study

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